Fiber Nuller:

detecting faint companions close to bright stars

Charles Hanot, Gene Serabyn, Stefan Martin, Dimitri Mawet, Bertrand Mennesson, Kurt Liewer, Frank Loya

Fiber Nuller:

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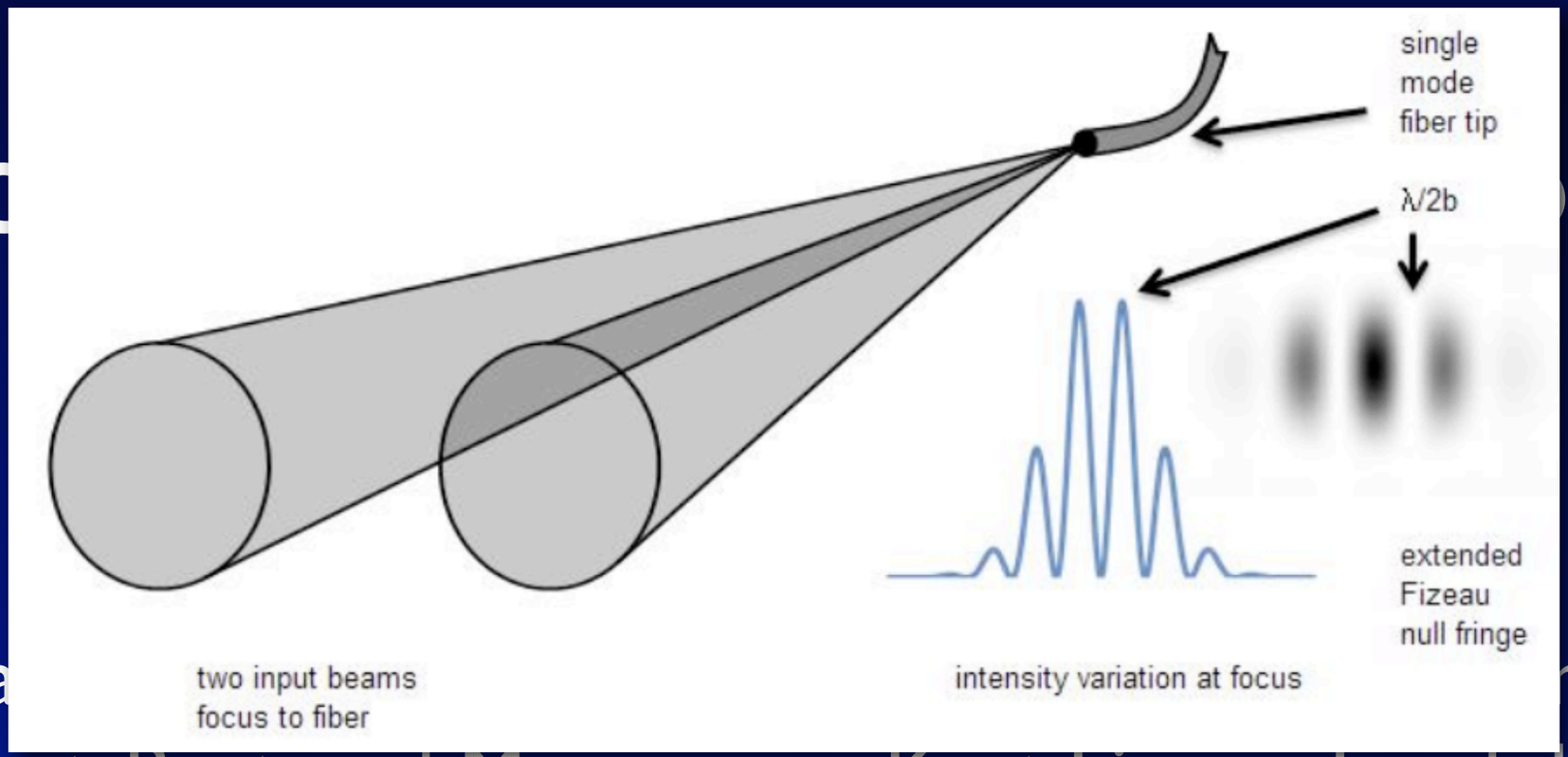

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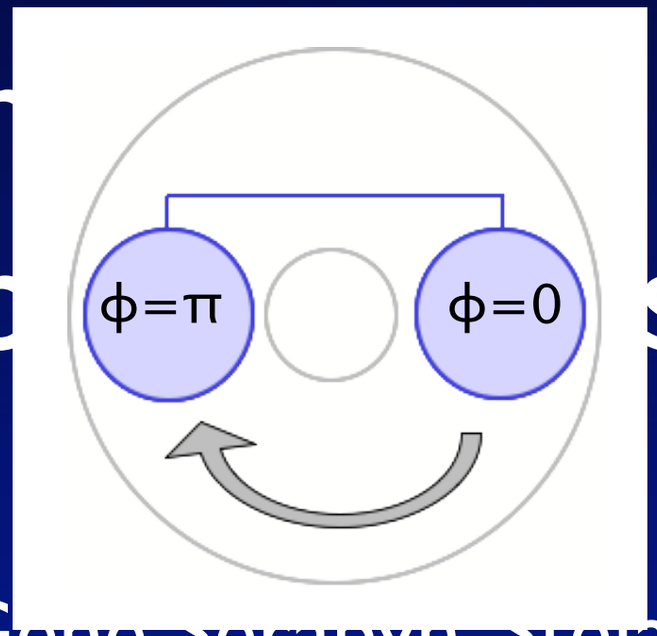

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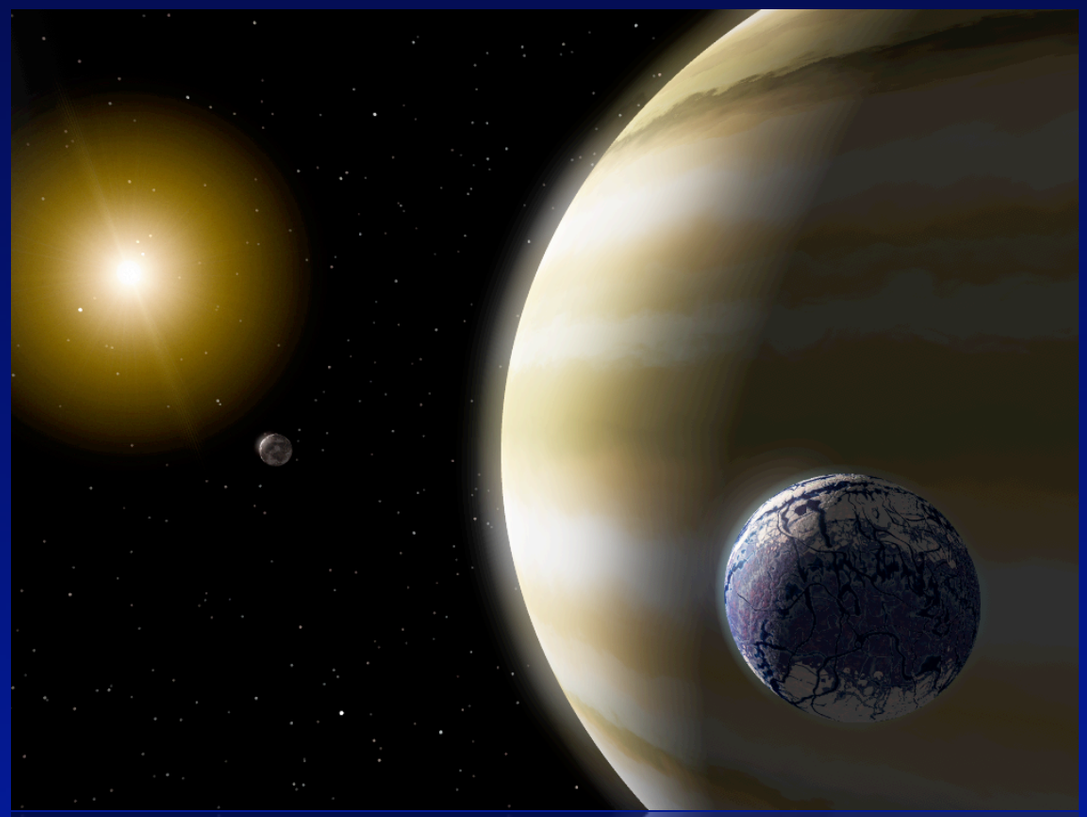
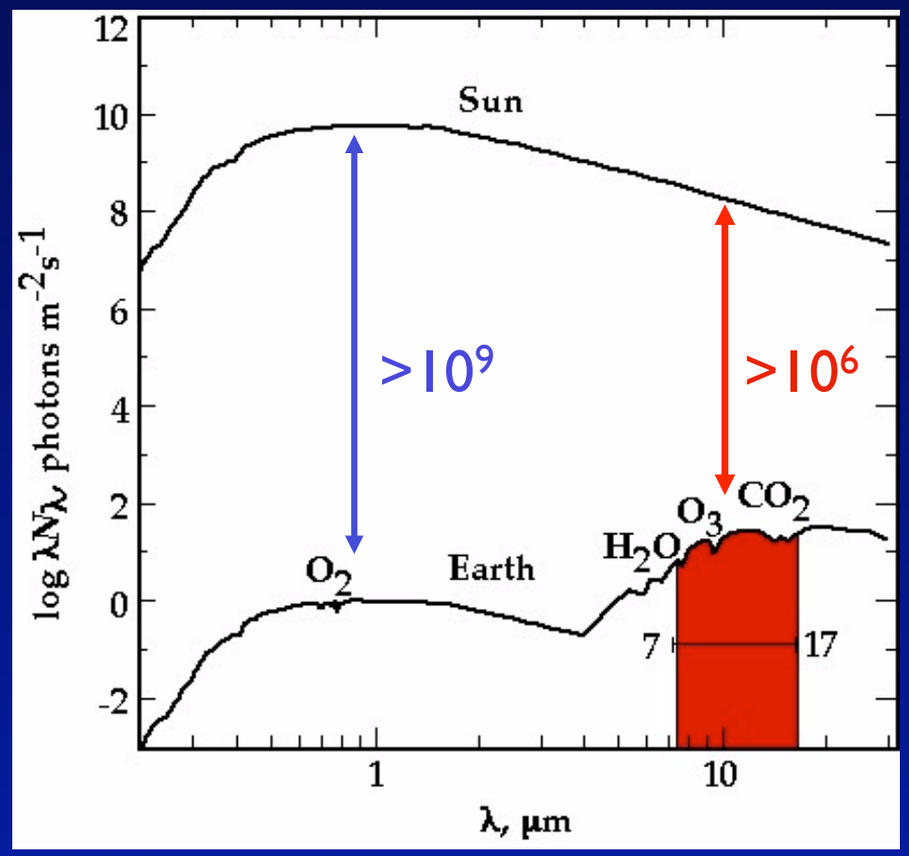


1.Introduction

- Direct imaging of high contrast objects:
  - Huge contrast ratio:
    - ➡Earth-like exoplanet:$2x10^7$ (10μm) & 10^{10} (visible)
    - ➡Brown dwarfs: 10^2 - 10^3
    - ➡Disks: 10^2 - 10^3
  - Small inner working angle
  - High angular resolution
  - High dynamic range
  - Wavefront quality



1.Introduction

2 complimentary solutions

Coronagraph:
- Wavelength: Visible
- 1 telescope of 4-8m
- Extinction ratio: 10^{-9}-10^{-10}

Nulling interferometer:
- Wavelength: Thermal IR
- 4 telescopes of 2-4m
- Extinction ratio: 10^{-5}-10^{-6}

1.Introduction

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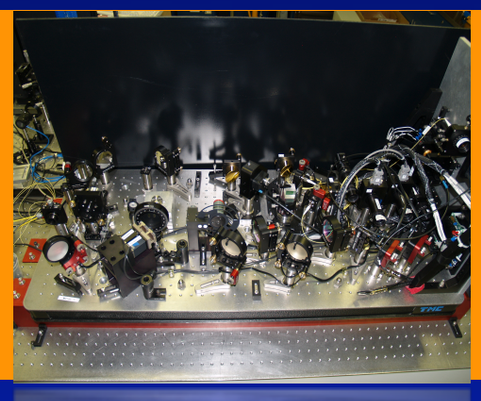
Nulling interferometer:
- Wavelength: Thermal IR
- 4 telescopes of 2-4m
- Extinction ratio: 10^{-5}-10^{-6}

Fiber Nuller coronagraph:
- Wavelength: K-band
- 1single 5m telescope, 2x1.5m sub-apertures
- Extinction ratio: 10^{-2}-10^{-3}

2.Fiber Nuller objectives

- Demonstrator for TPF-I/Darwin :
  - ➡First ground-based rotating nuller
- Coronagraphy :
  - ➡Very low inner working angle
- Science :
  - ➡Detection of faint off-axis companions



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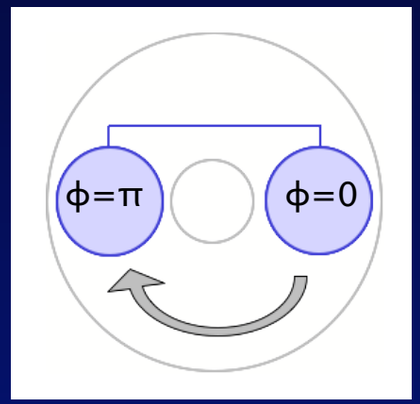

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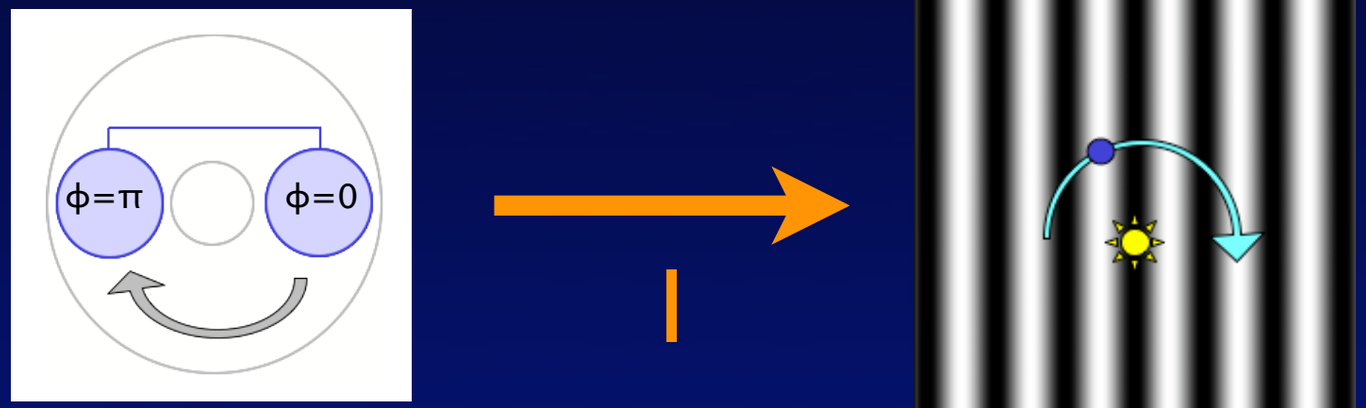

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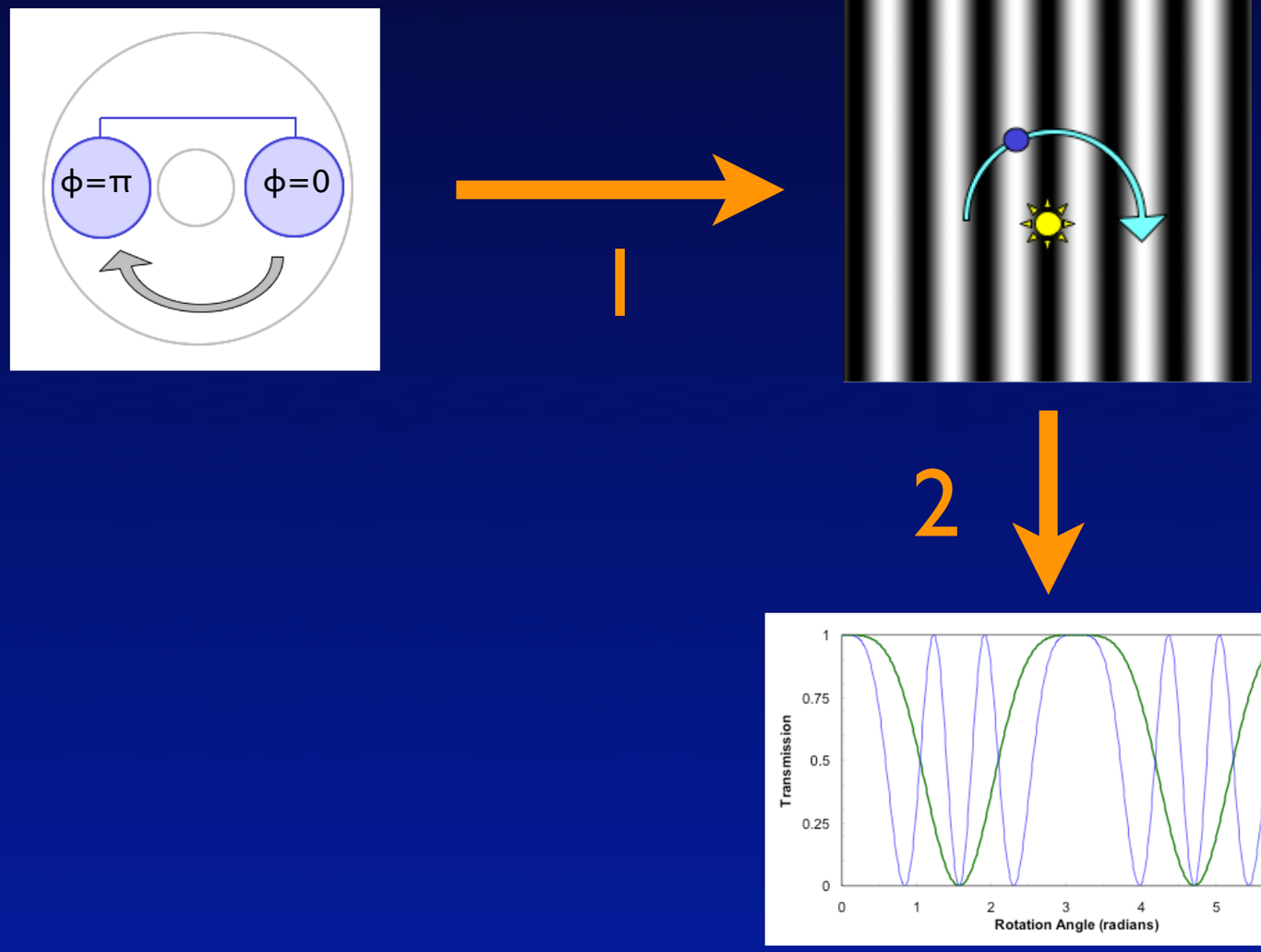

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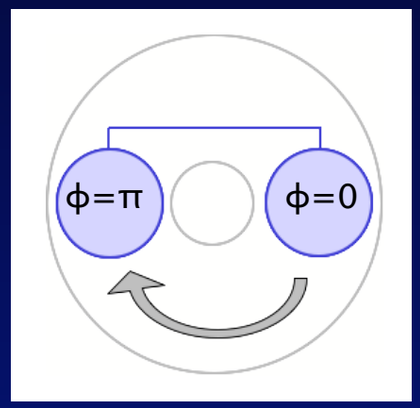

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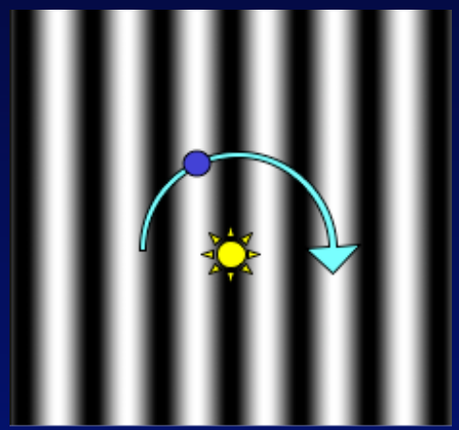

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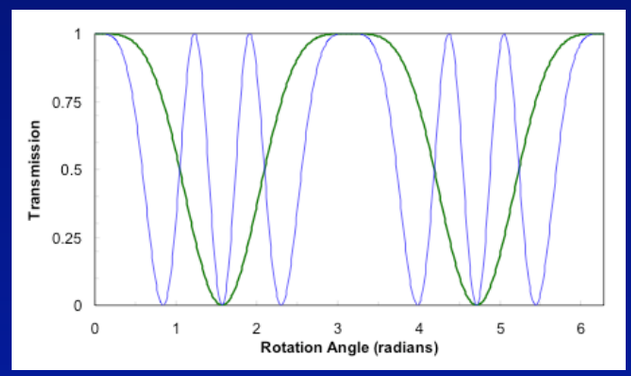

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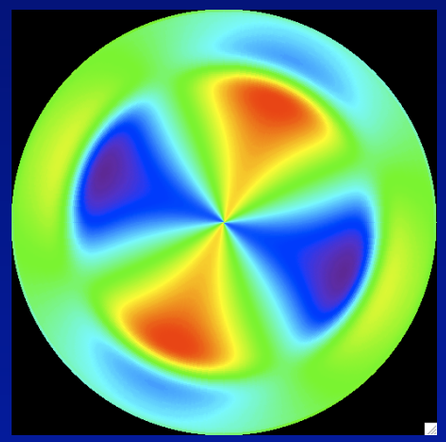

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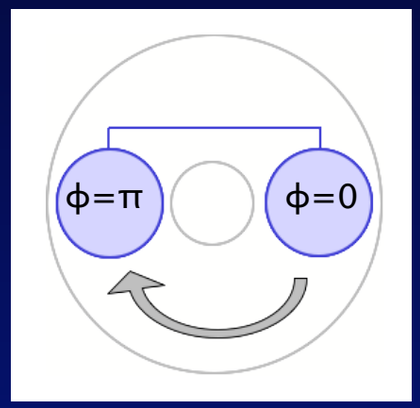
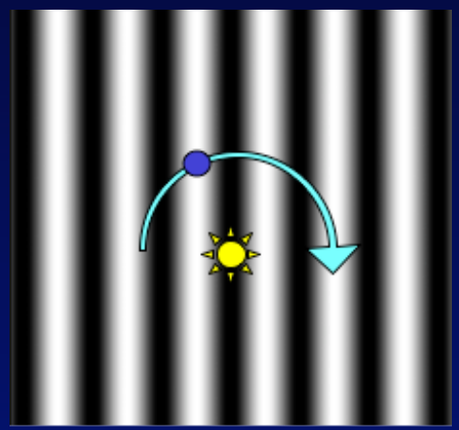


1



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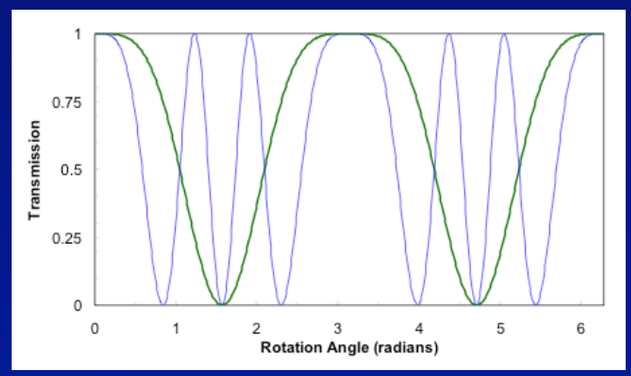

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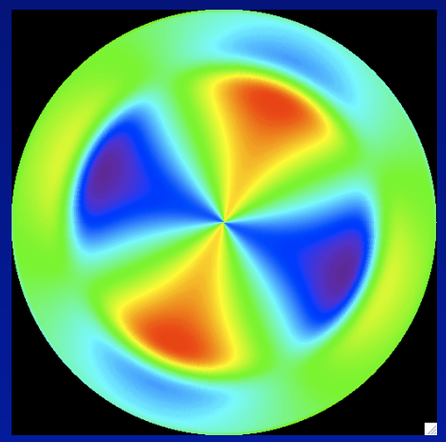
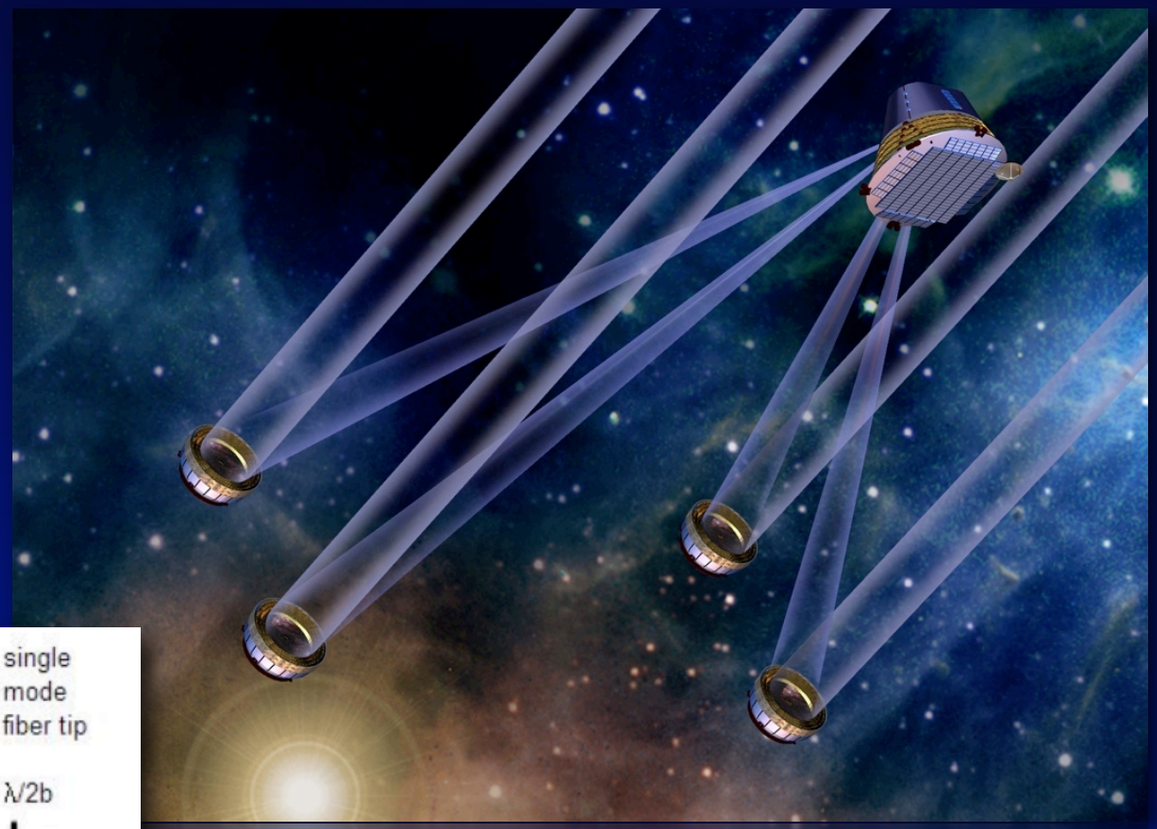
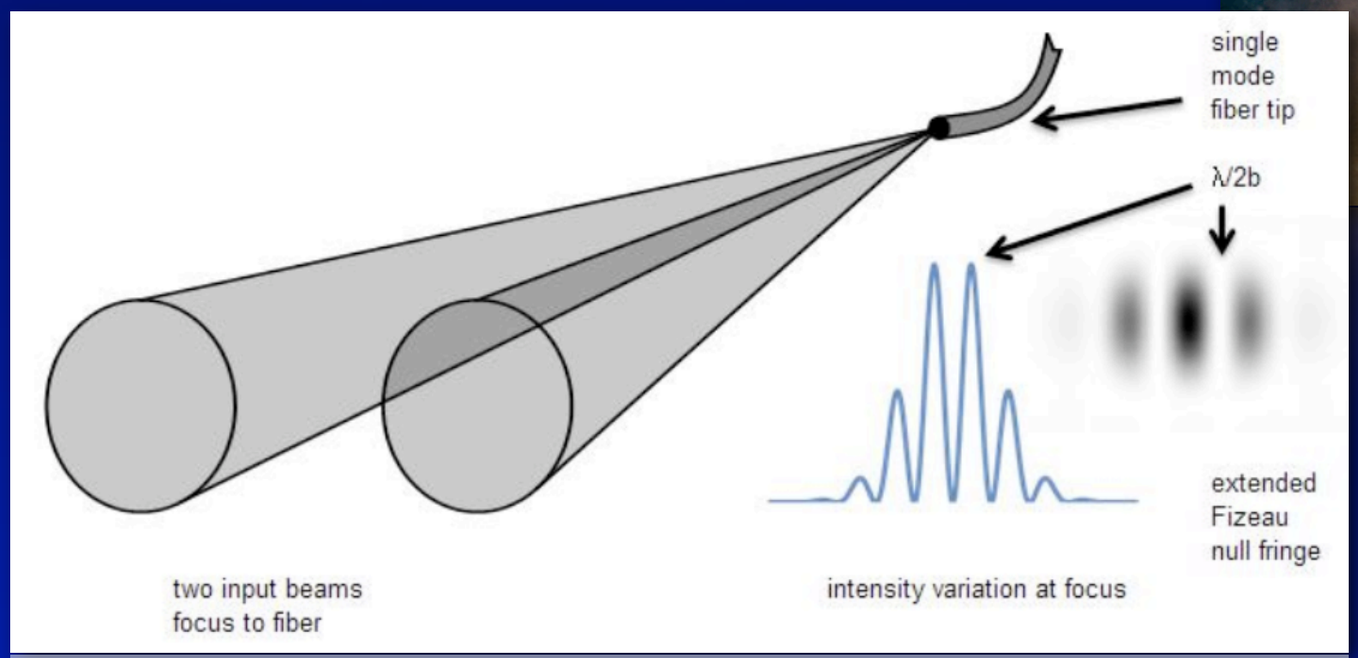


First experiment to demonstrate this technique

2.Fiber Nuller objectives

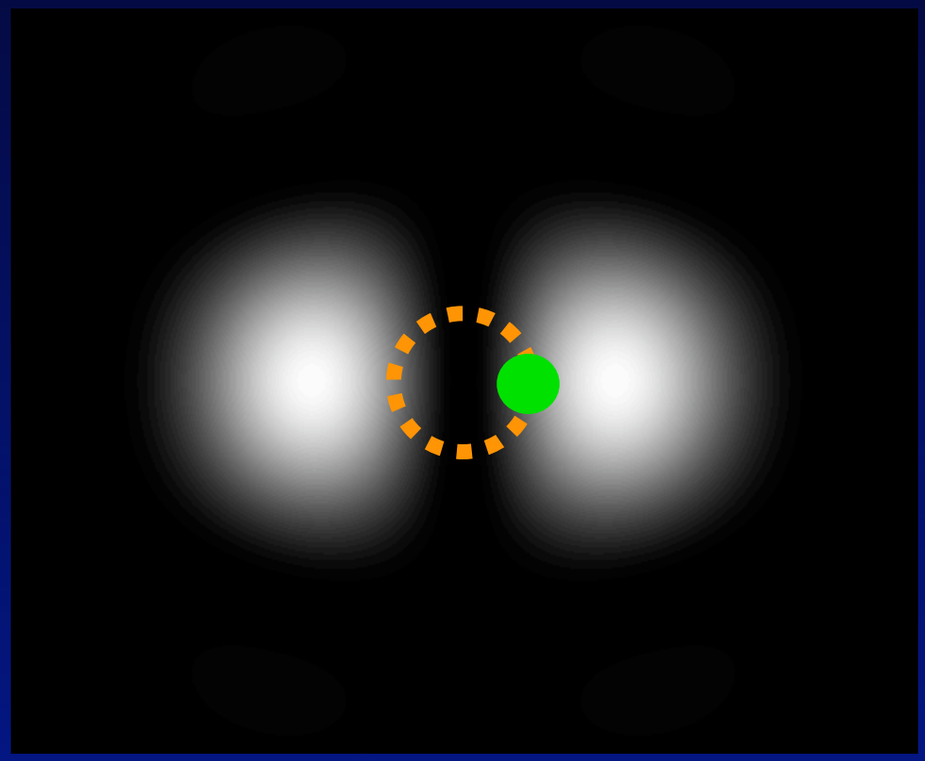
- Demonstrator for TPF-I/Darwin :
  - ➡Off-axis/multi-axial recombination





2.Fiber Nuller objectives

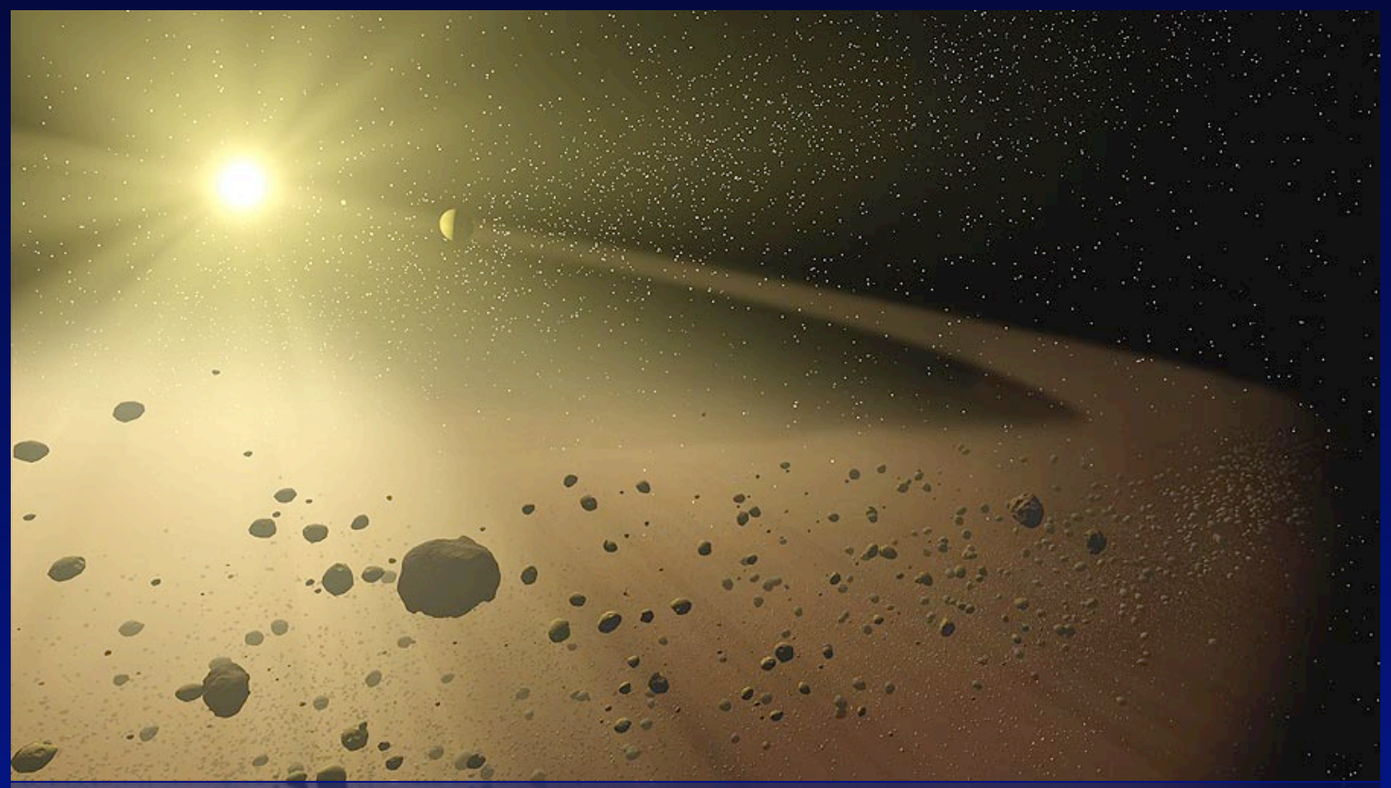
- "Coronagraphy" :
  - ➡Very low inner working angle



- Spatial resolution: λ/2B = 65 mas (k-band, B=3.5m)
- Half transmission: λ/4B = 32.5 mas

2.Fiber Nuller objectives

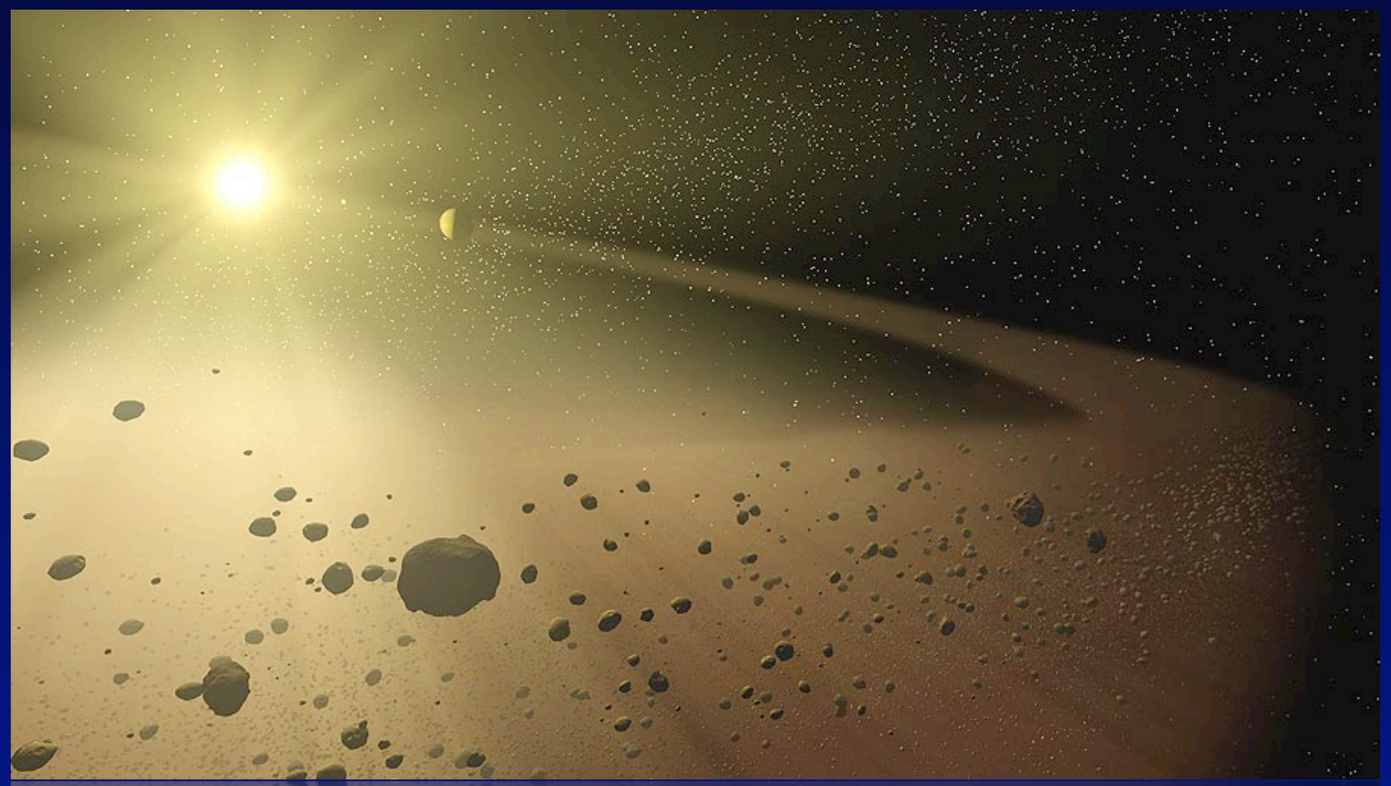
- Science :
  - ➡Detection of faint off-axis companions



- Potential targets :
  - ➡Contrast 100:1 to 1000:1(now)
  - ➡Near future, contrast 10^4 (maybe better)
  - ➡Angular separation < 150 mas

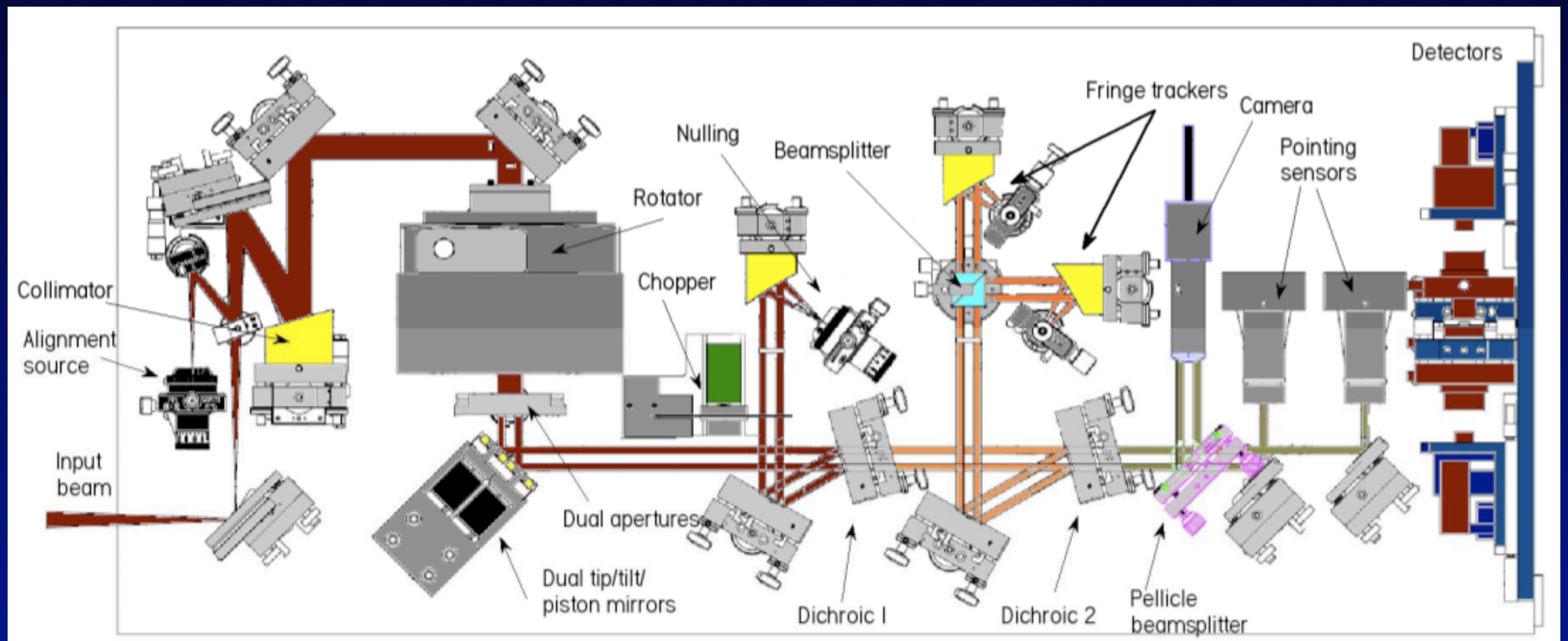
2.Fiber Nuller objectives

- Science :
  - ➡Observation of circumstellar disks



- Potential targets :
  - ➡Survey of hot material around mK<5 stars with known IR excess

3.Layout of the instrument



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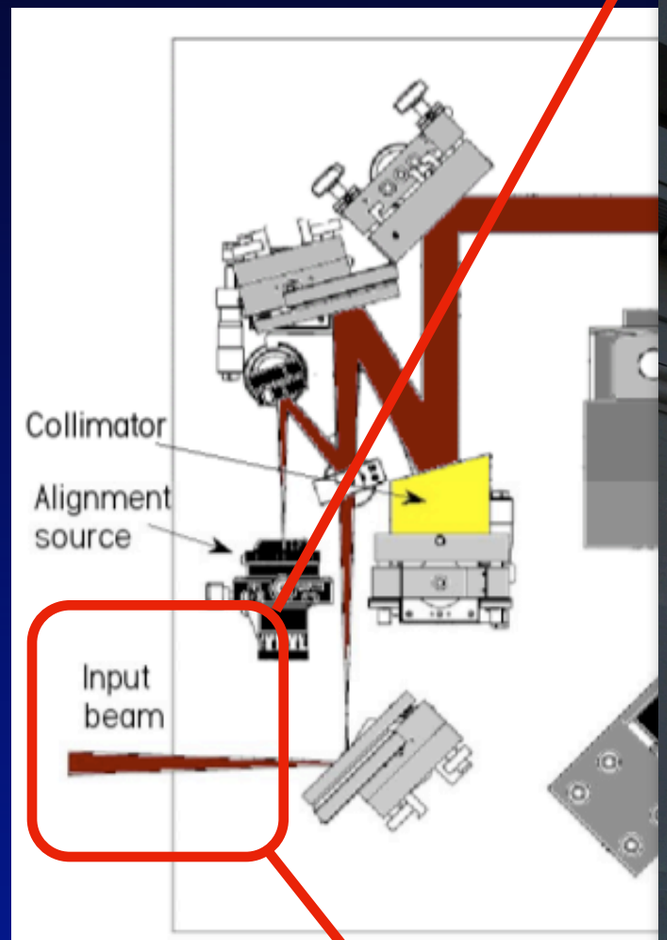

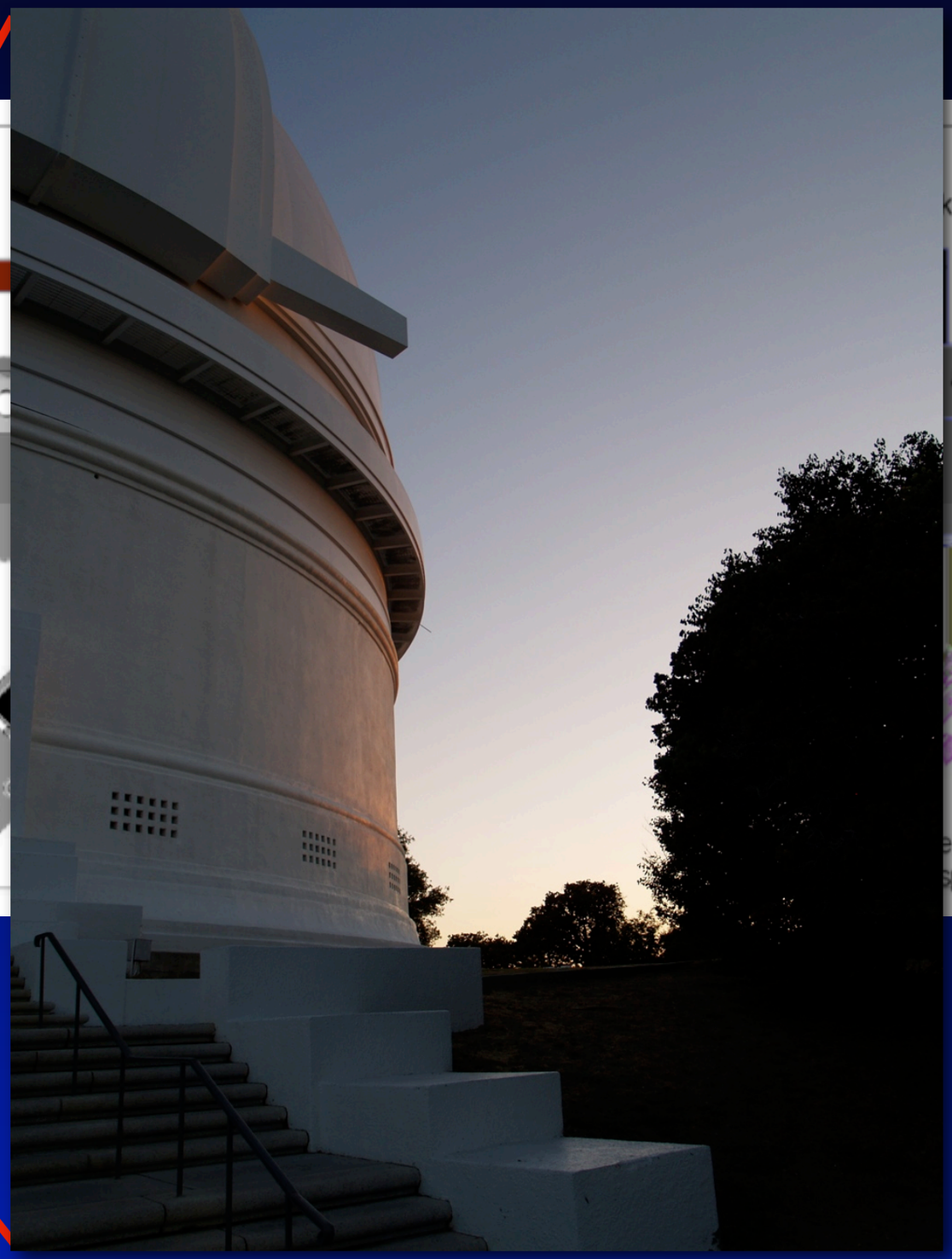

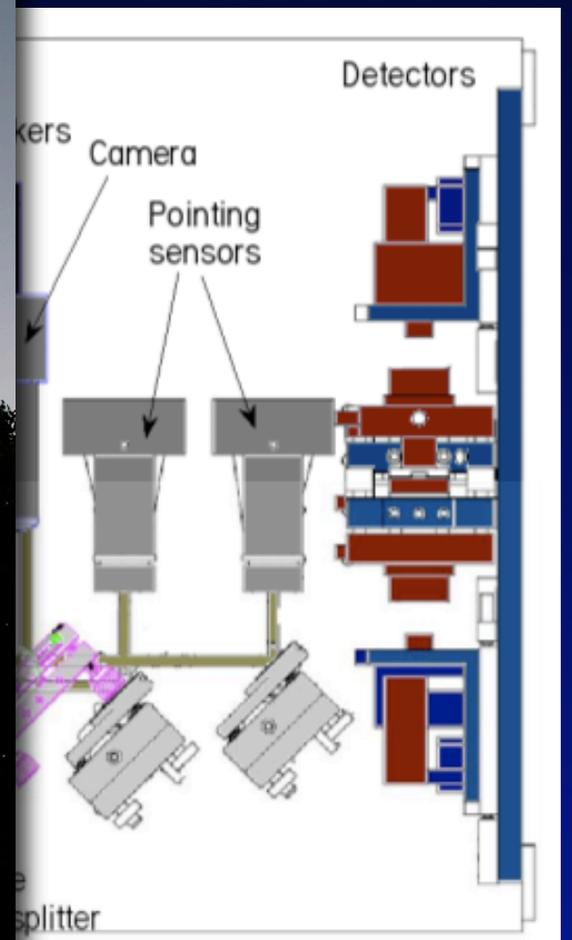

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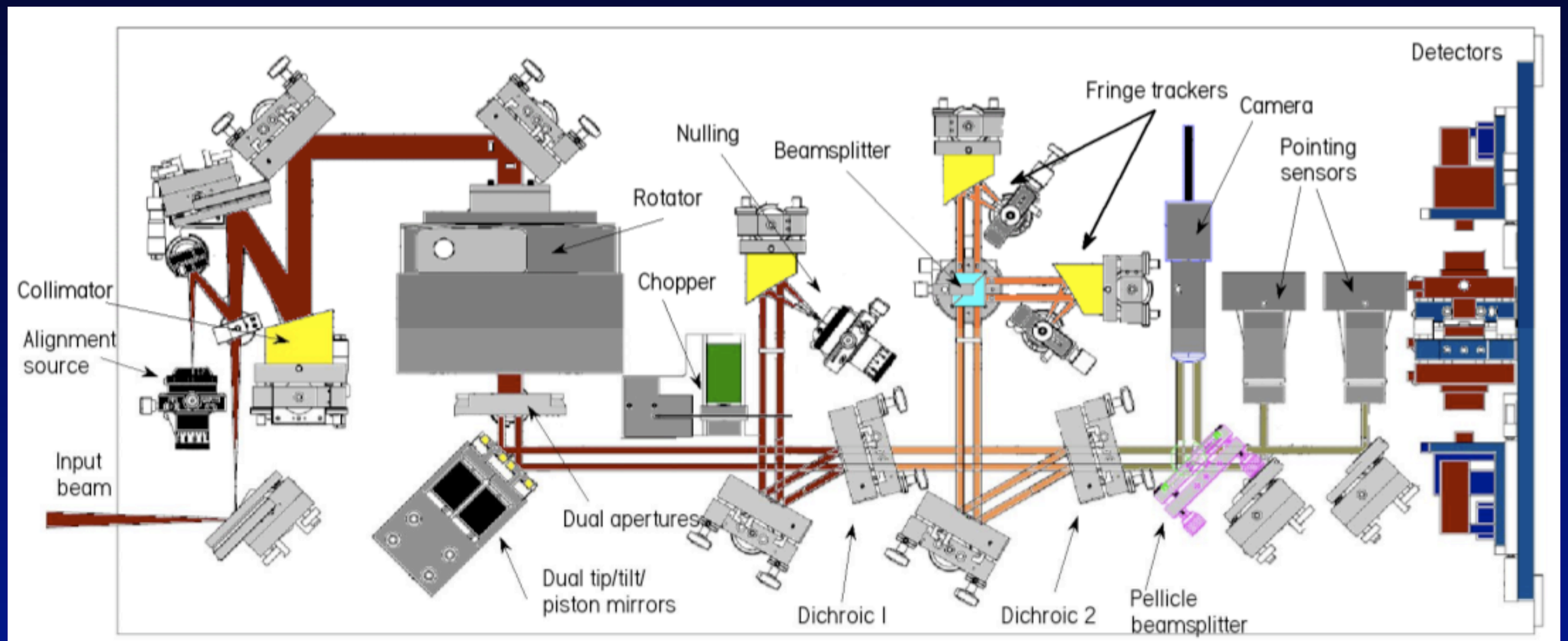

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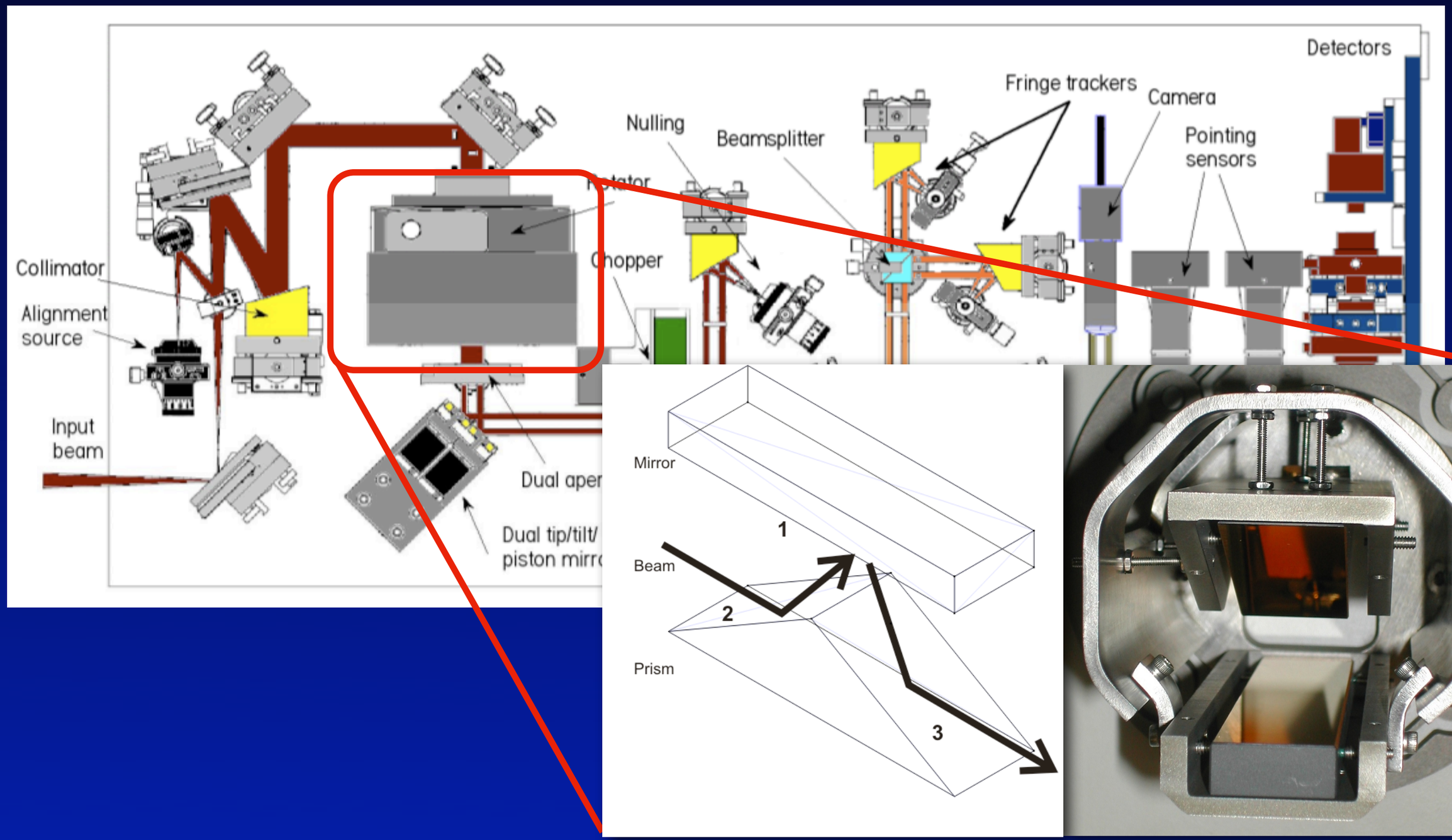

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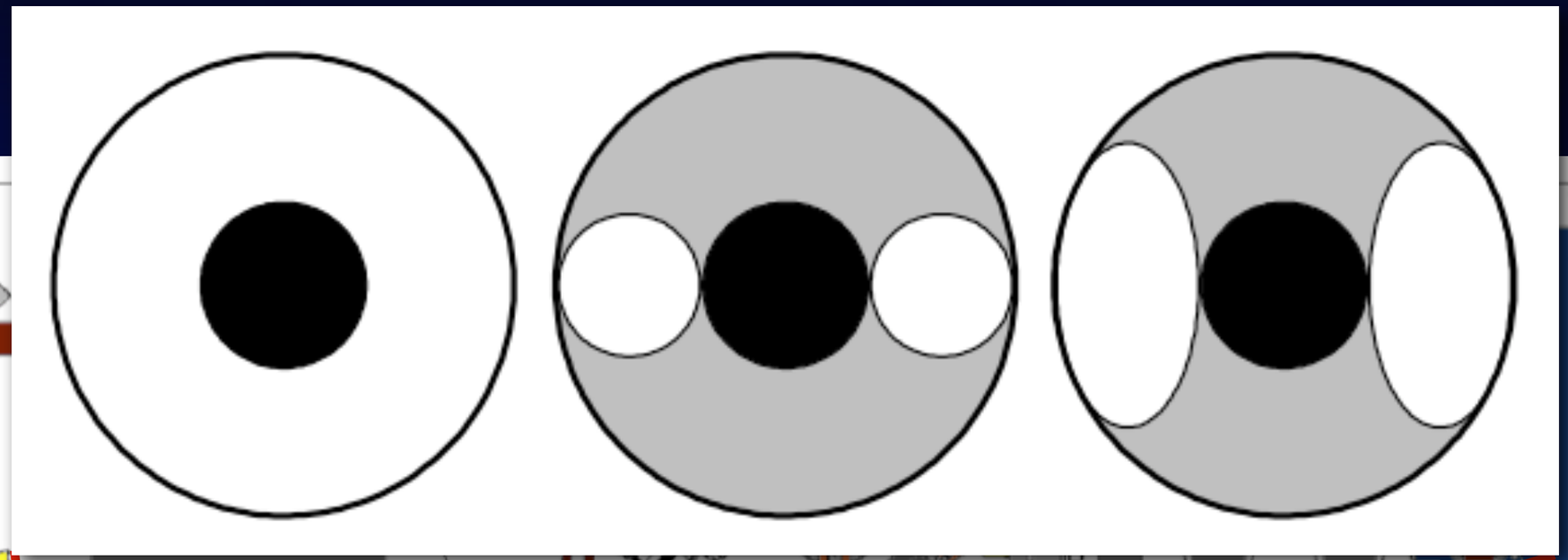

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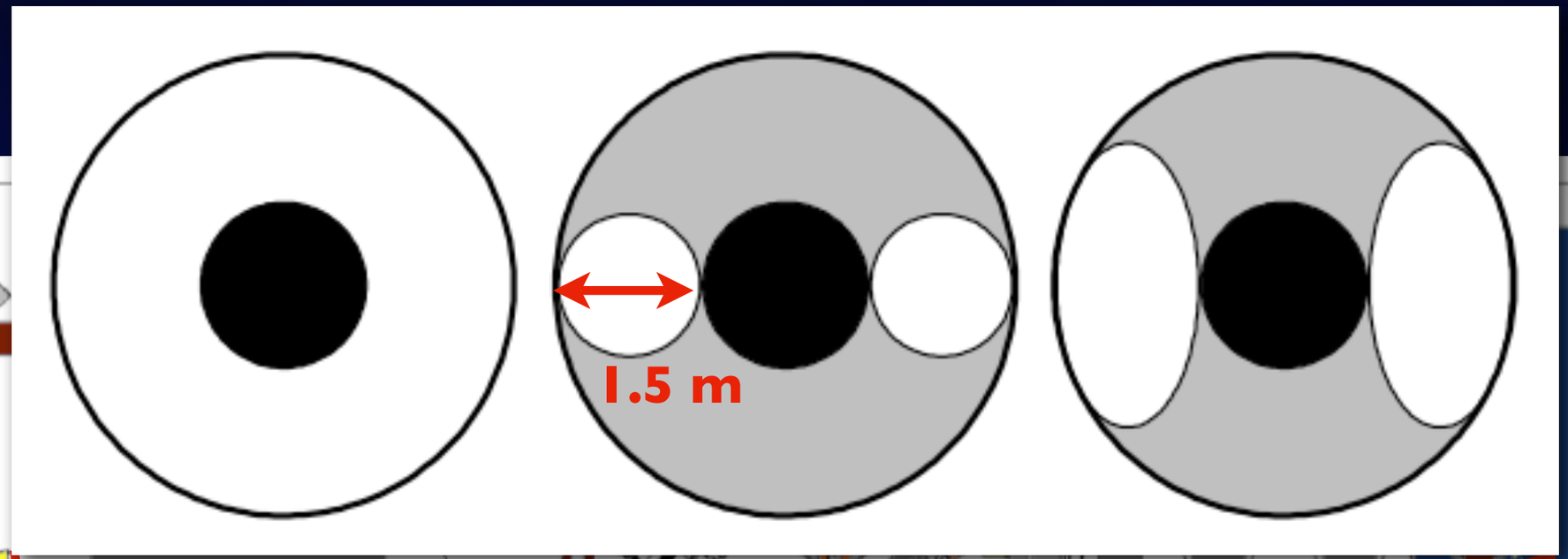

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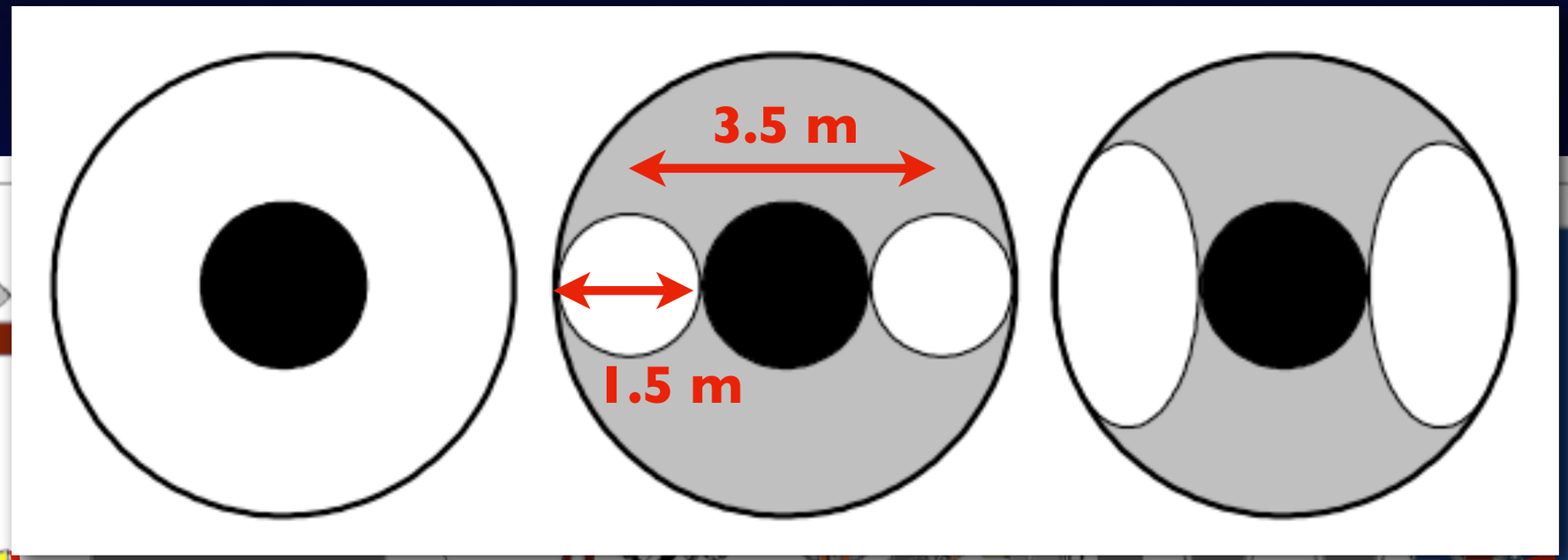

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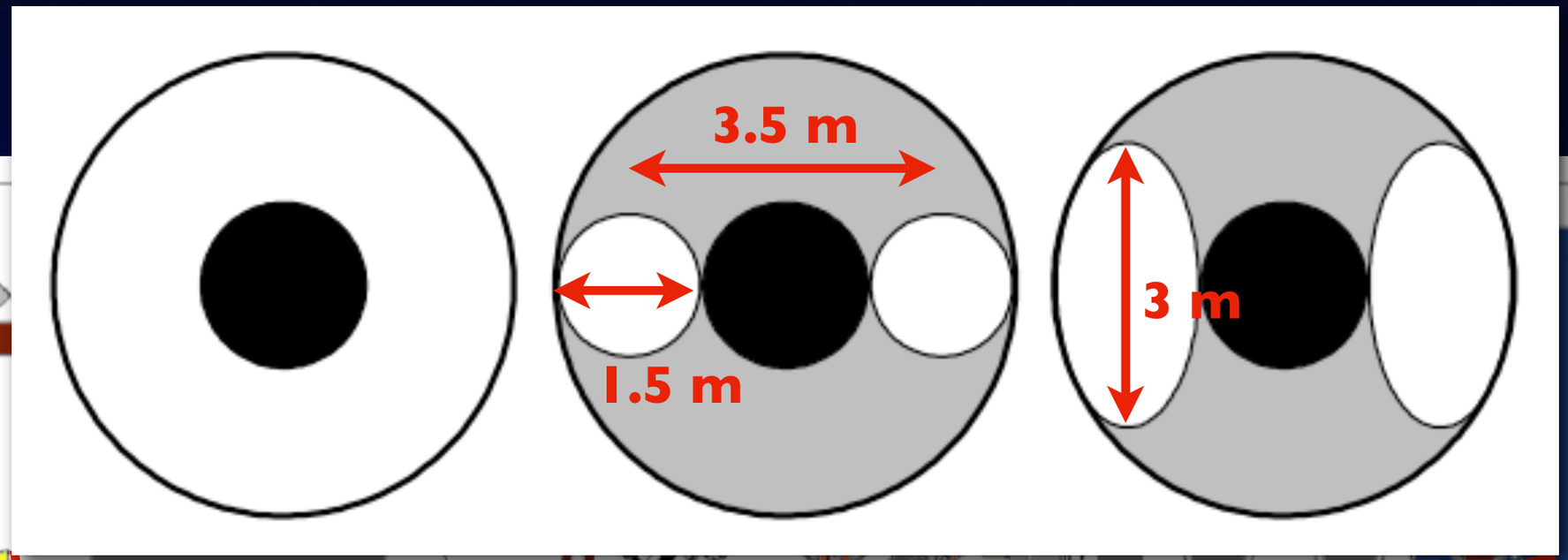

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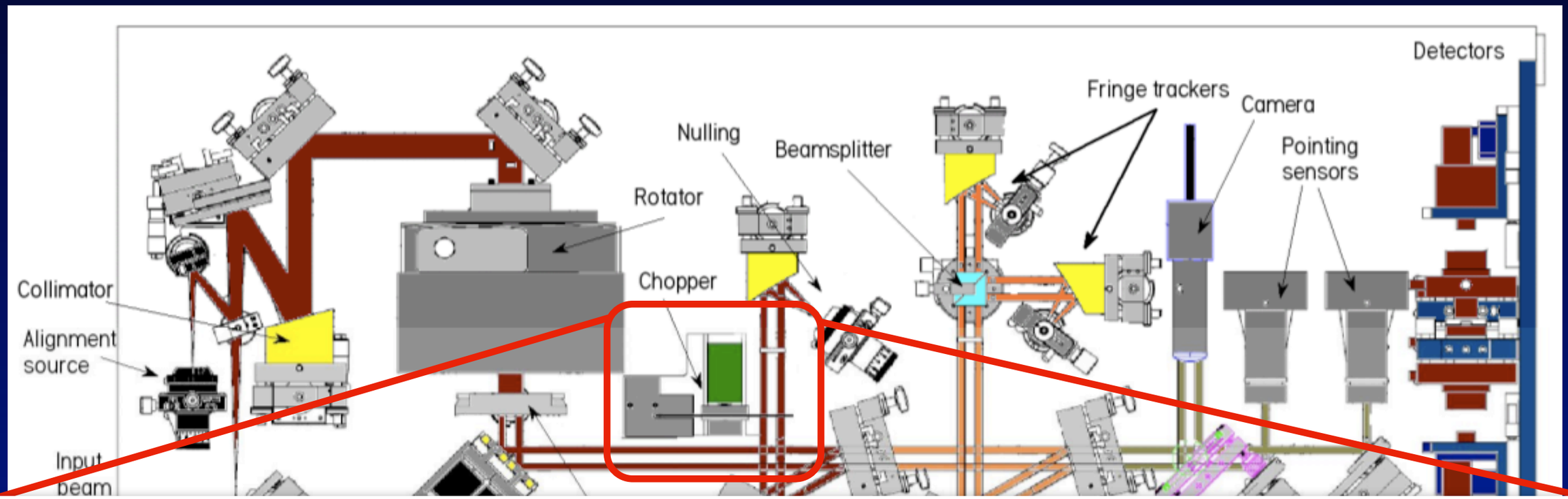
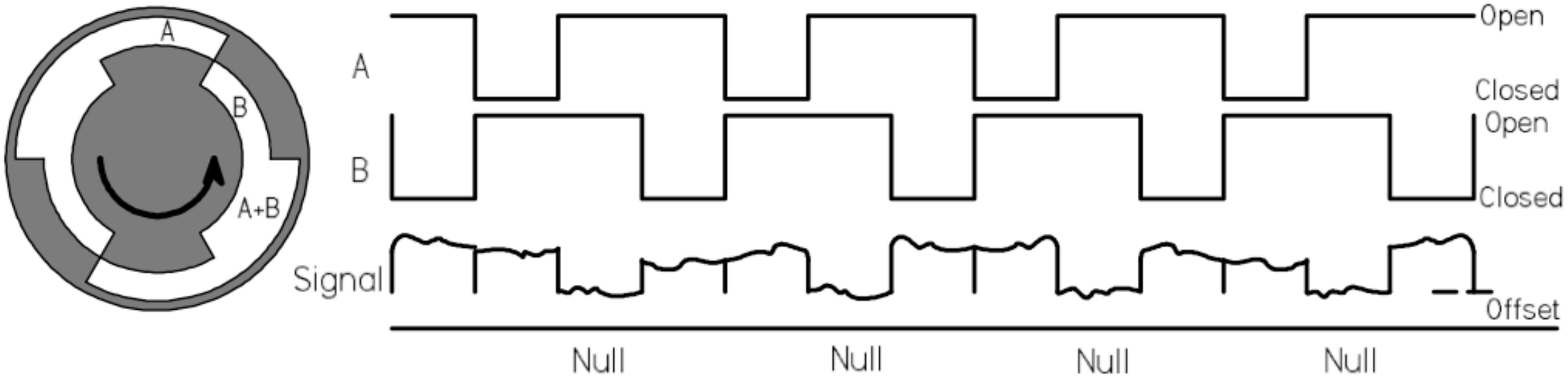
$$Null = \frac{I_{ab}}{I_a + I_b + 2\sqrt{I_a I_b}}$$





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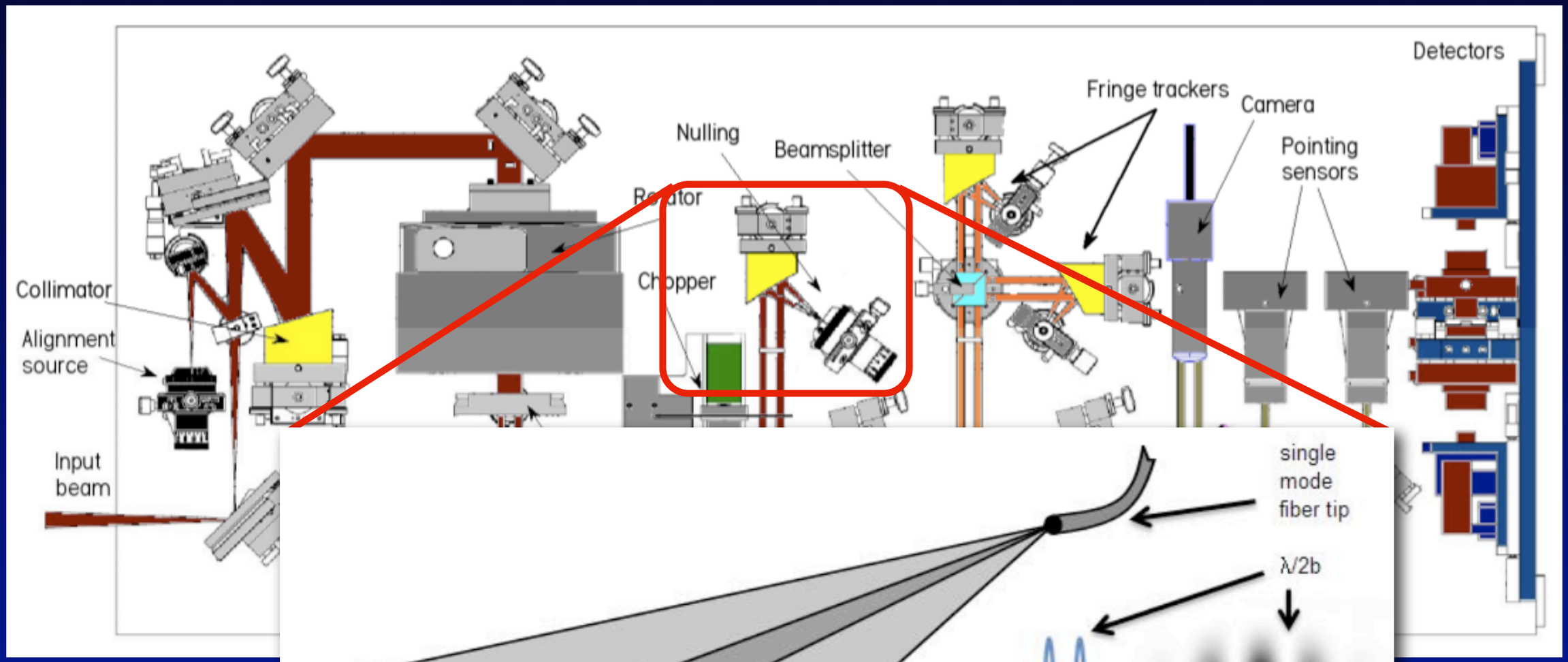

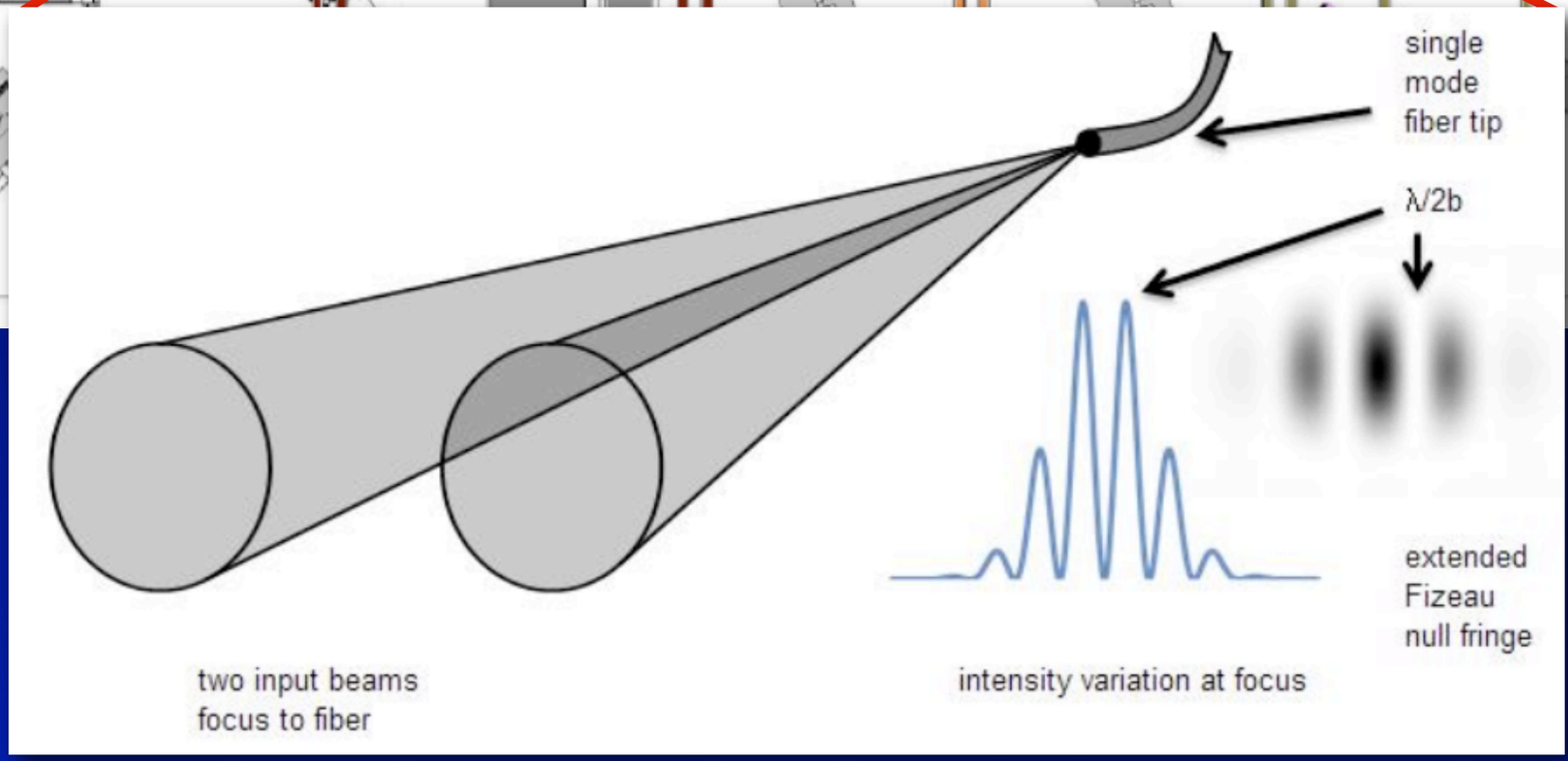

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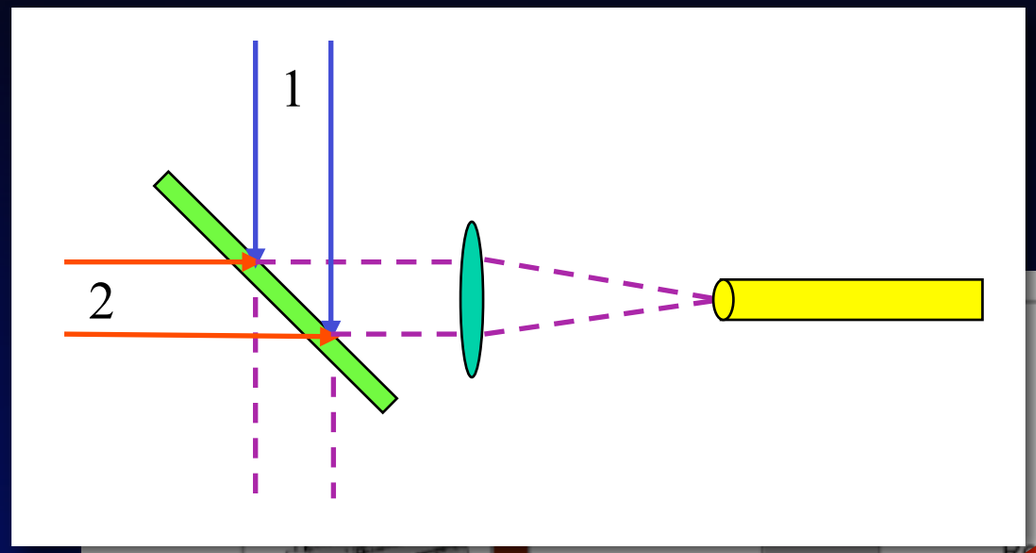

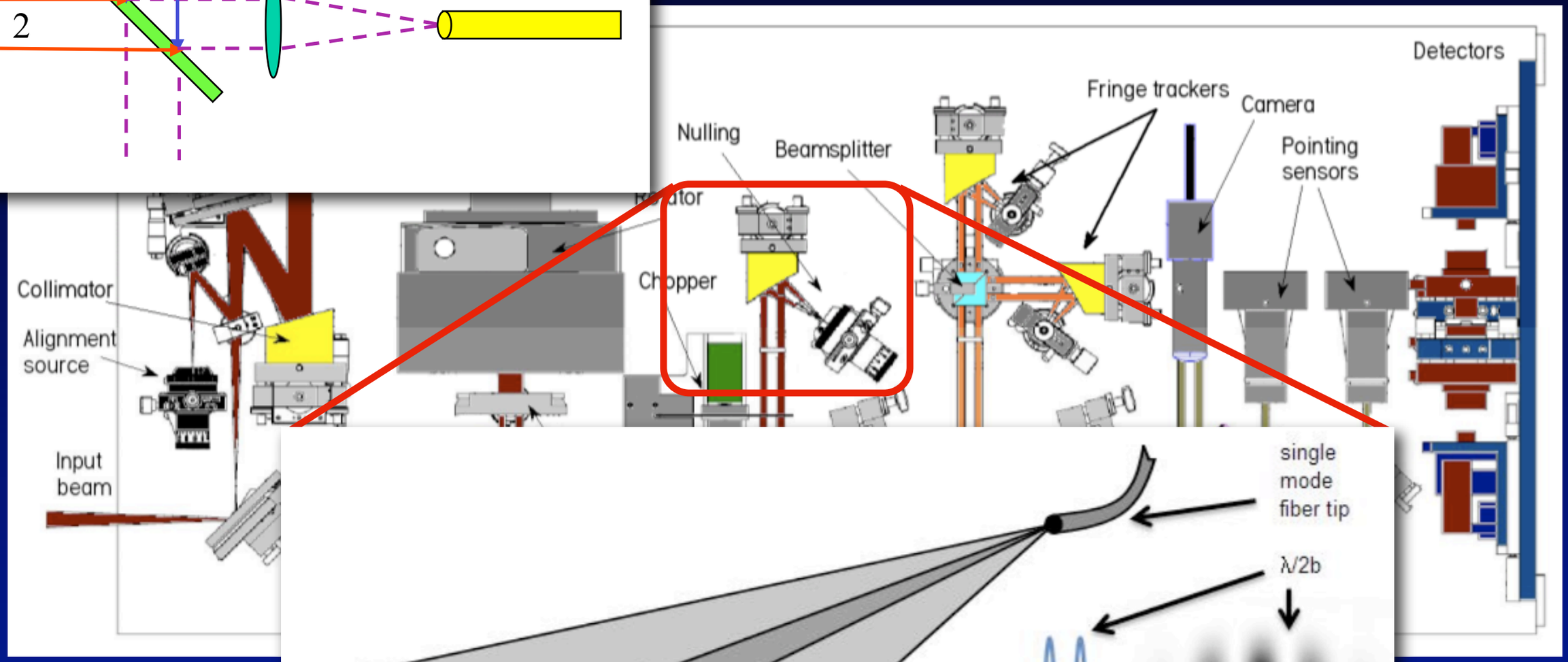

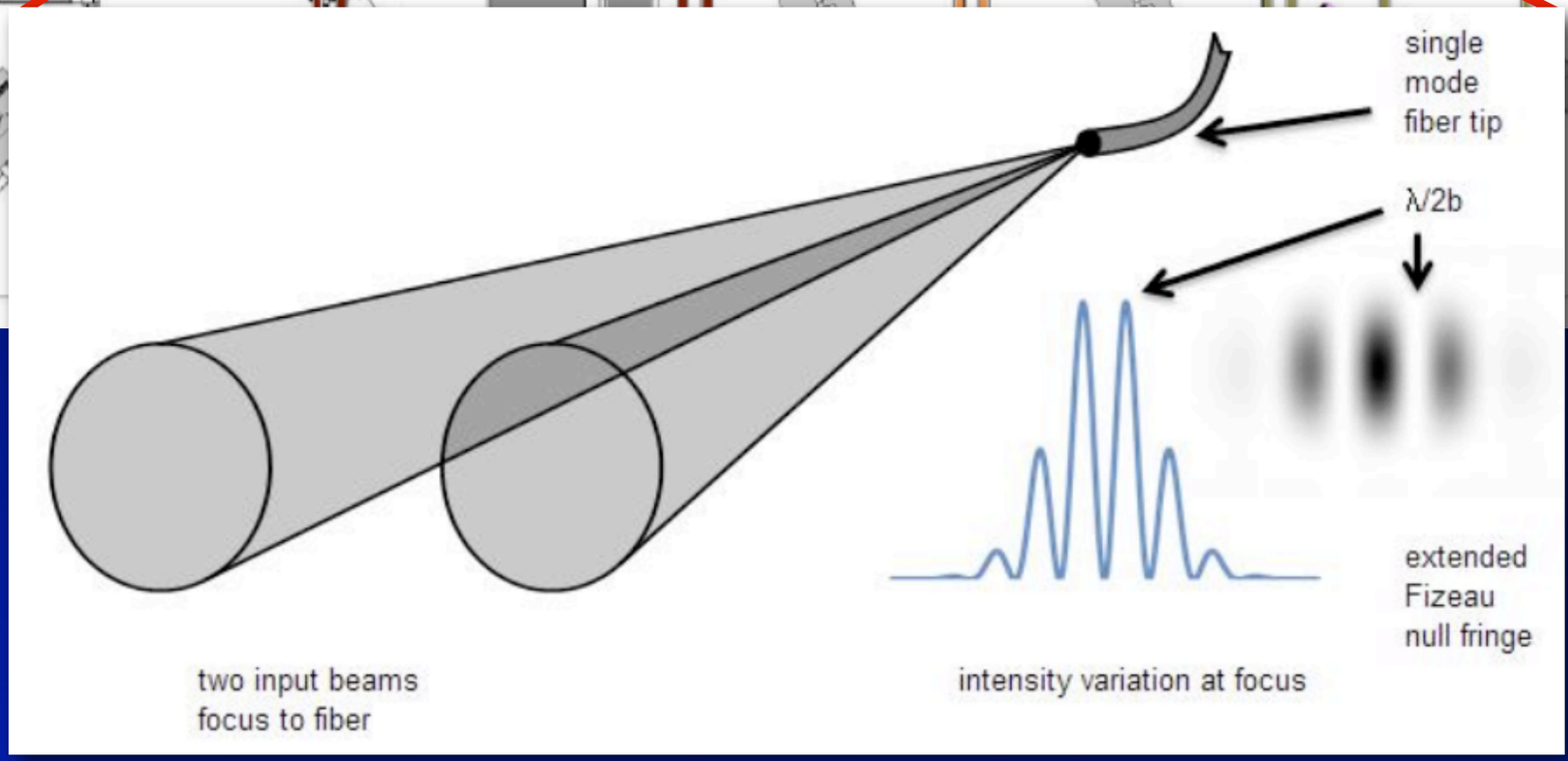

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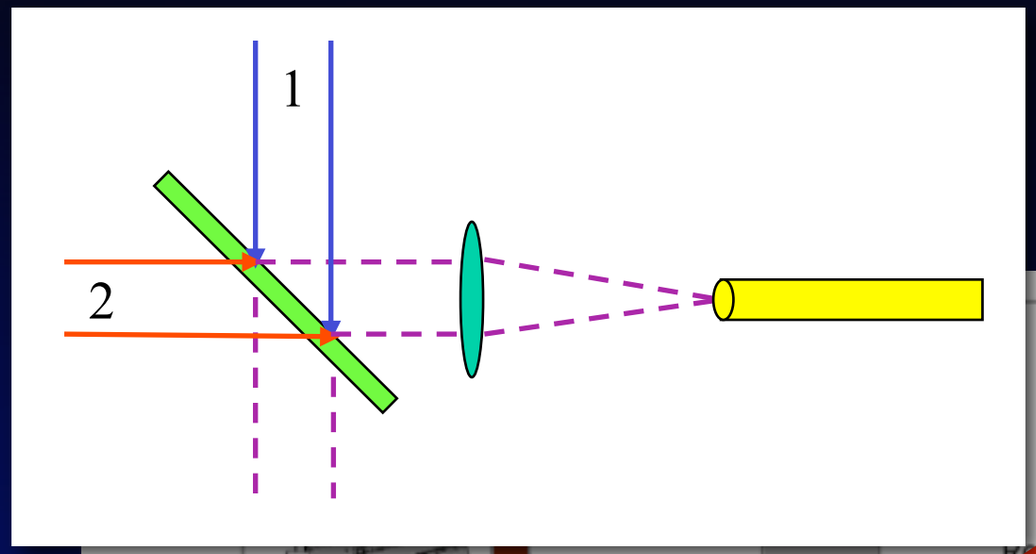

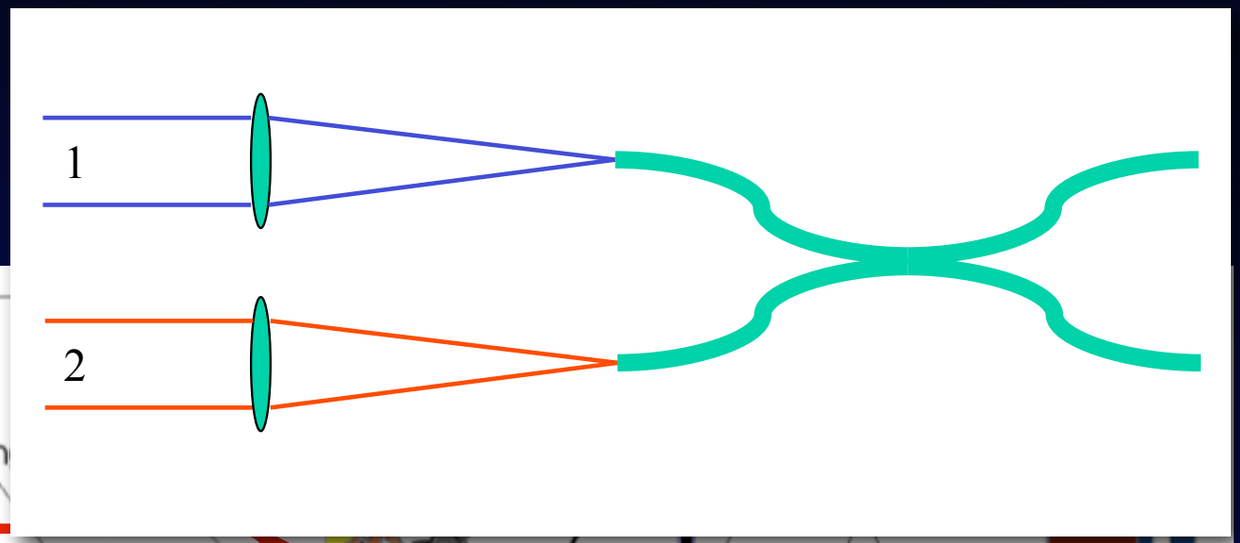

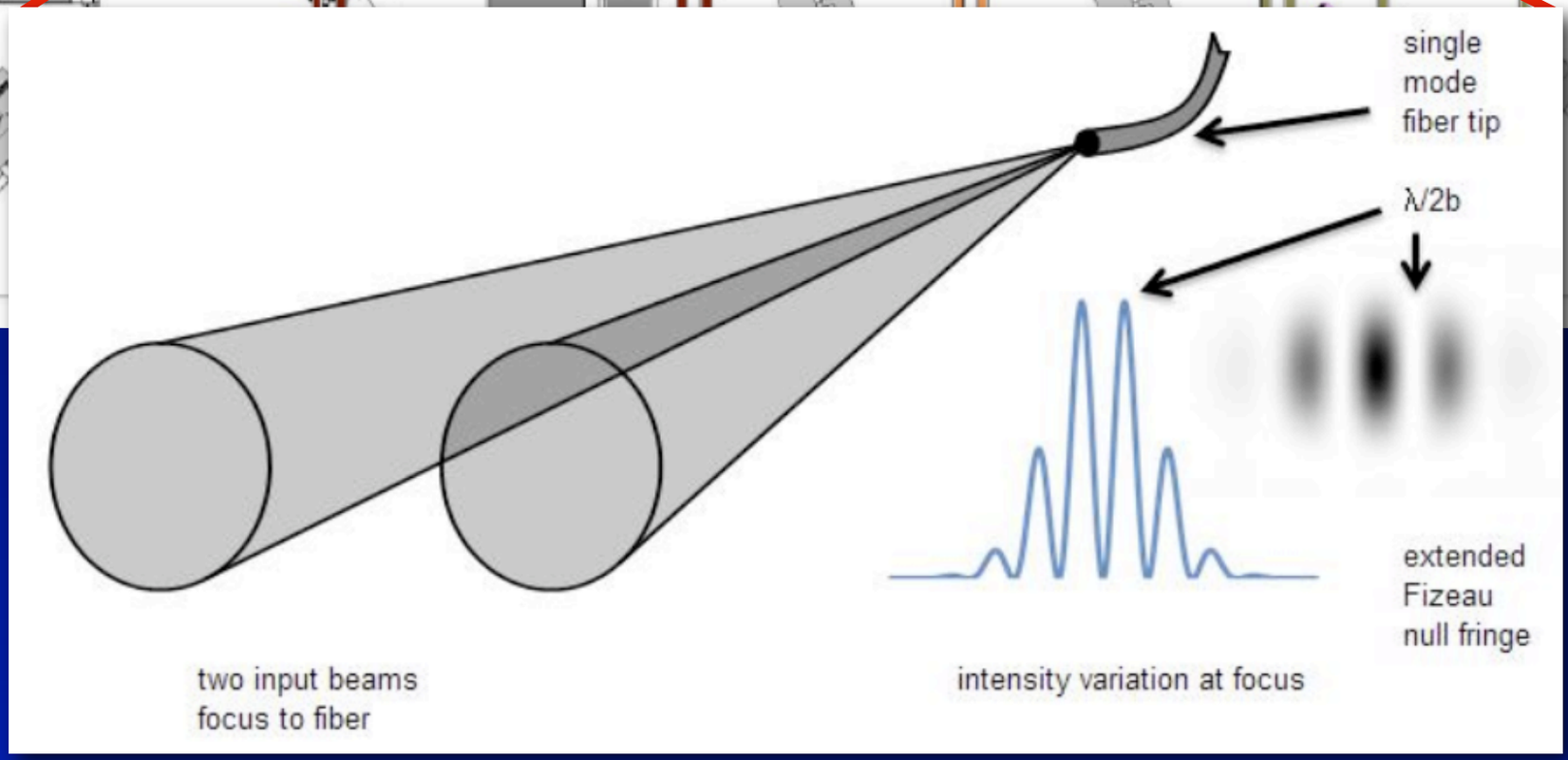

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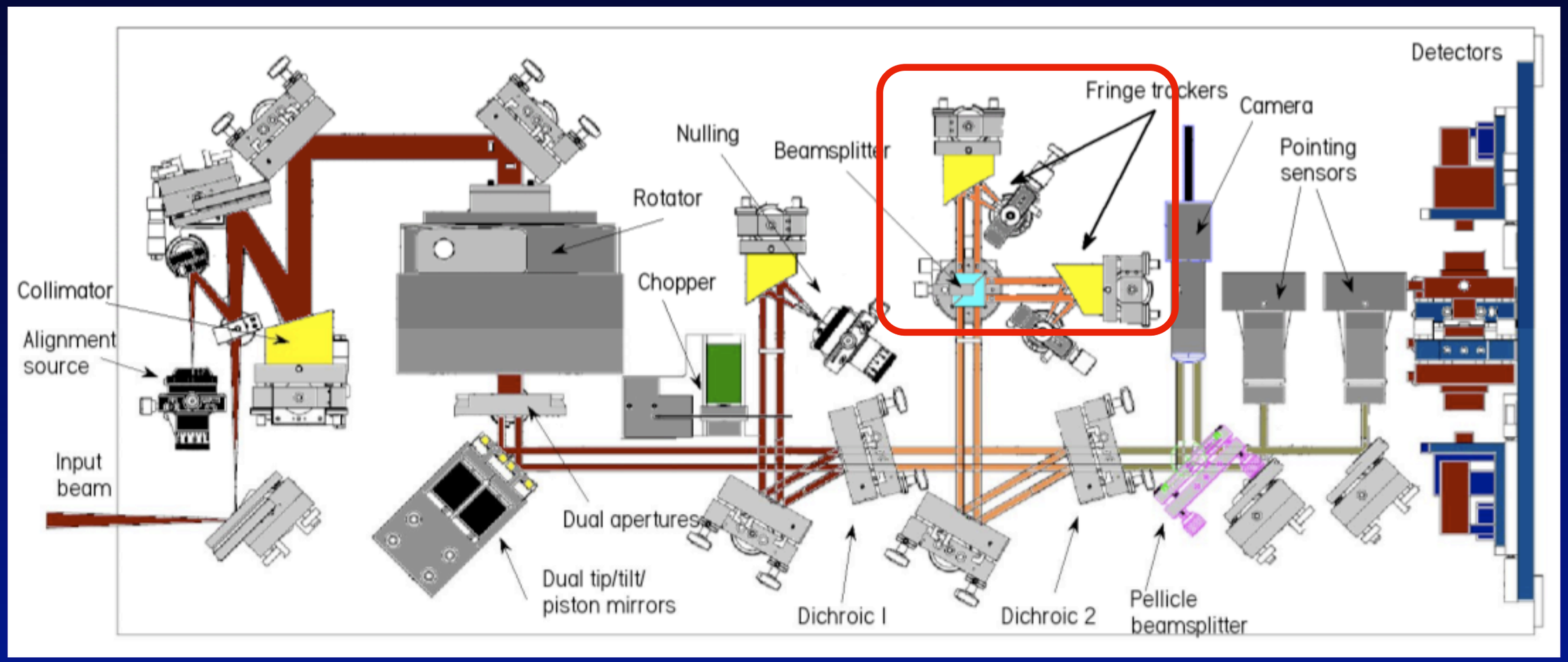

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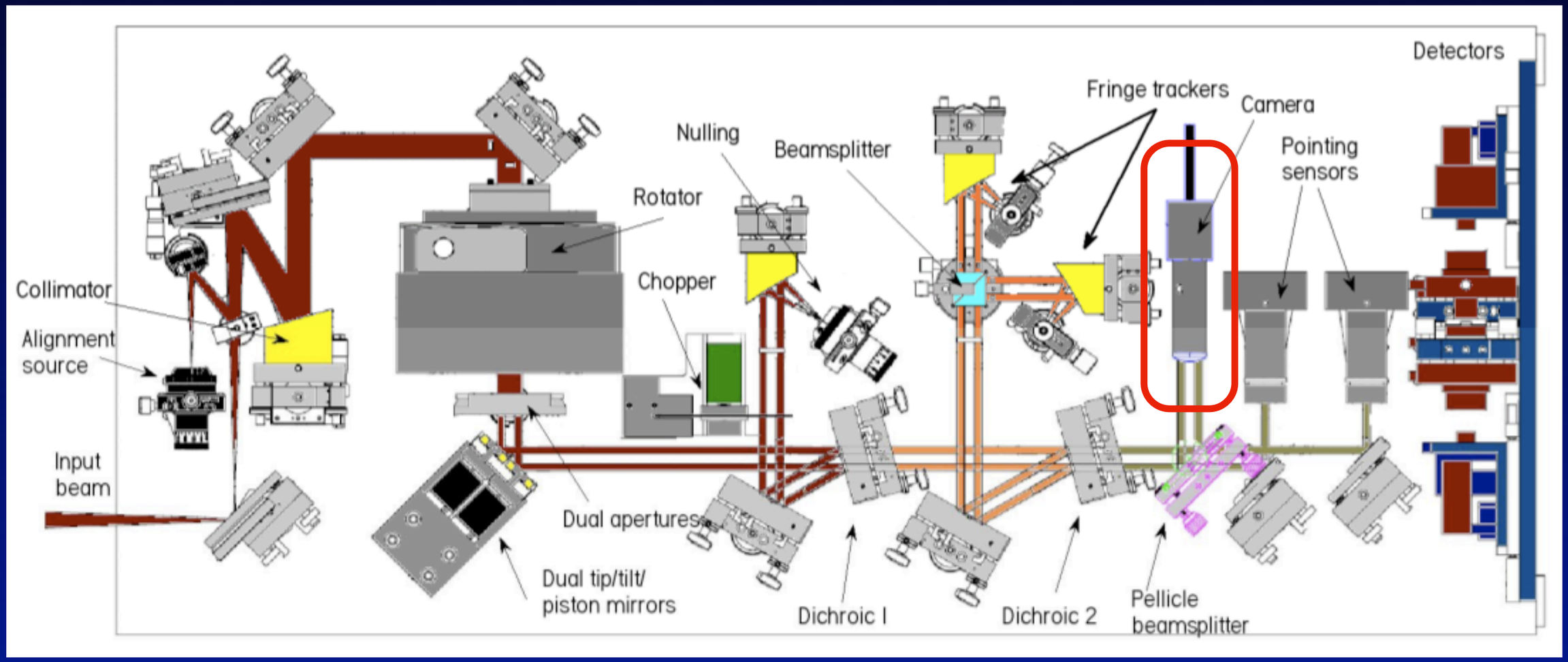

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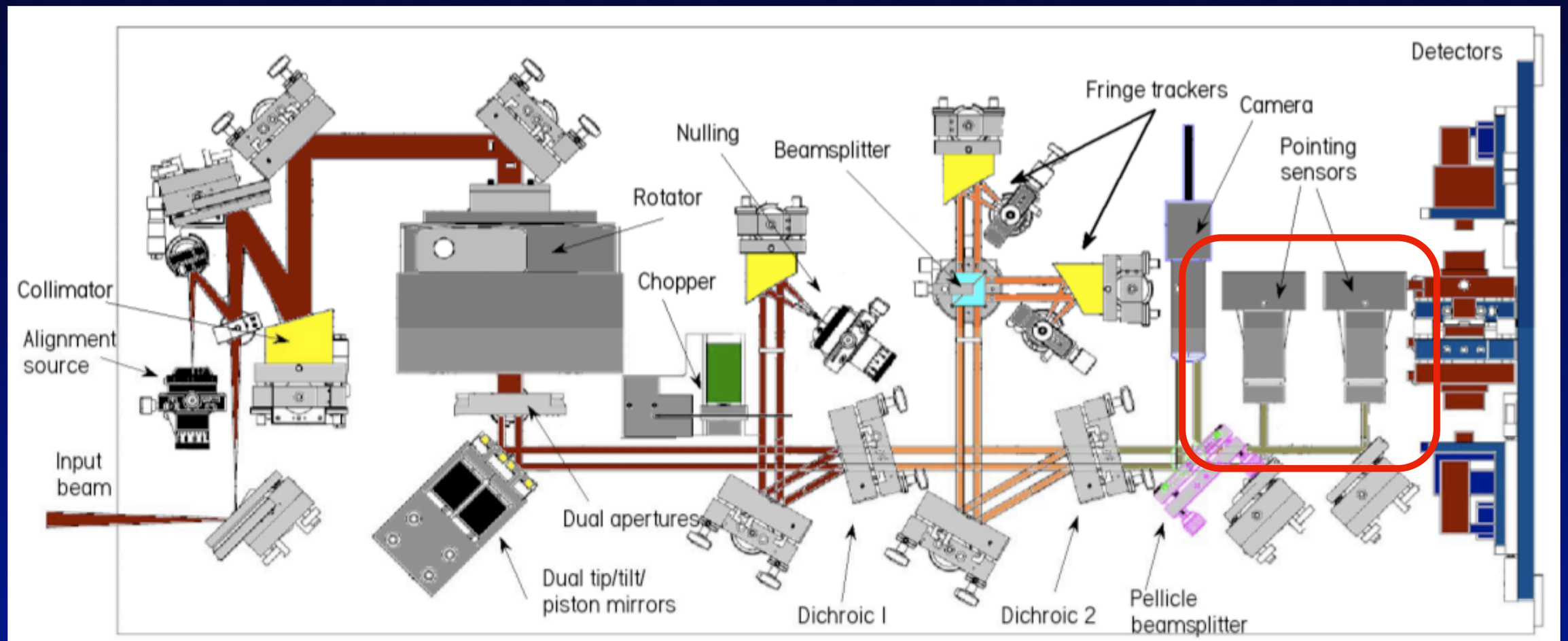

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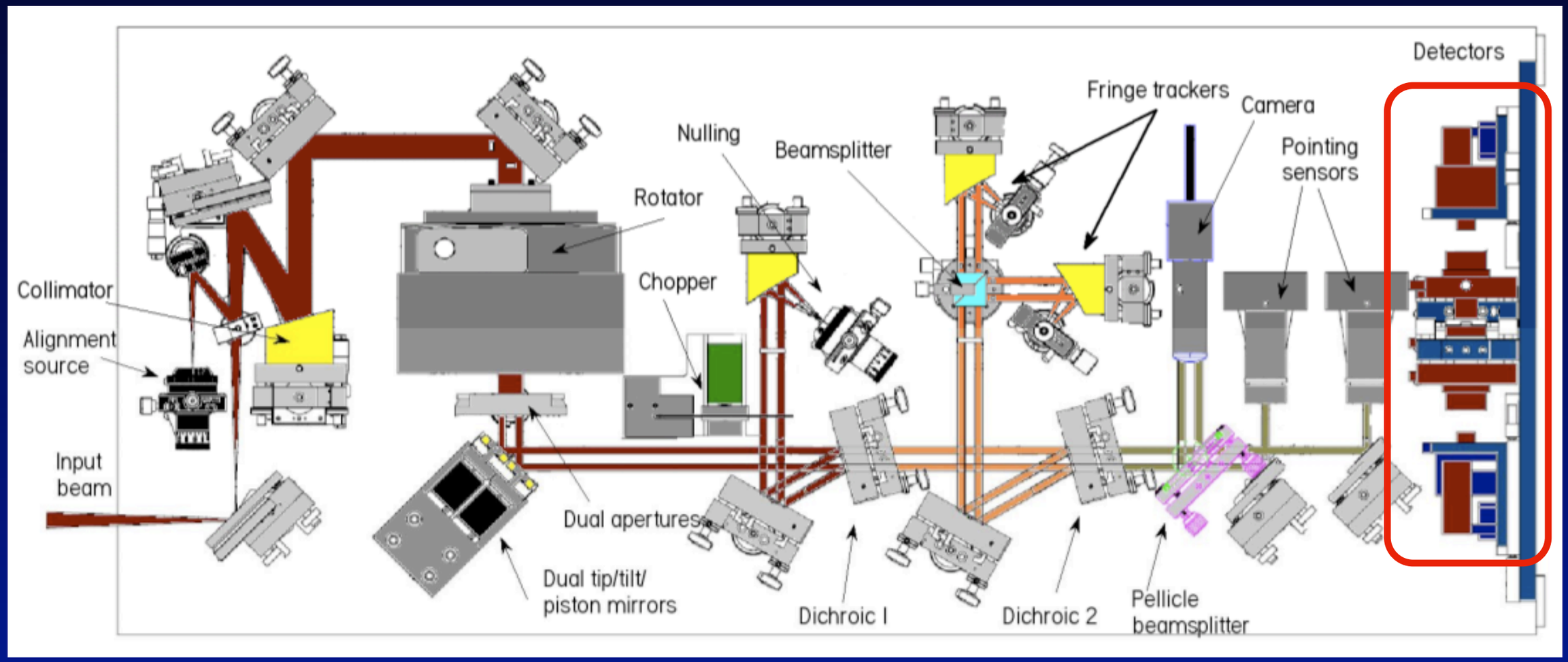
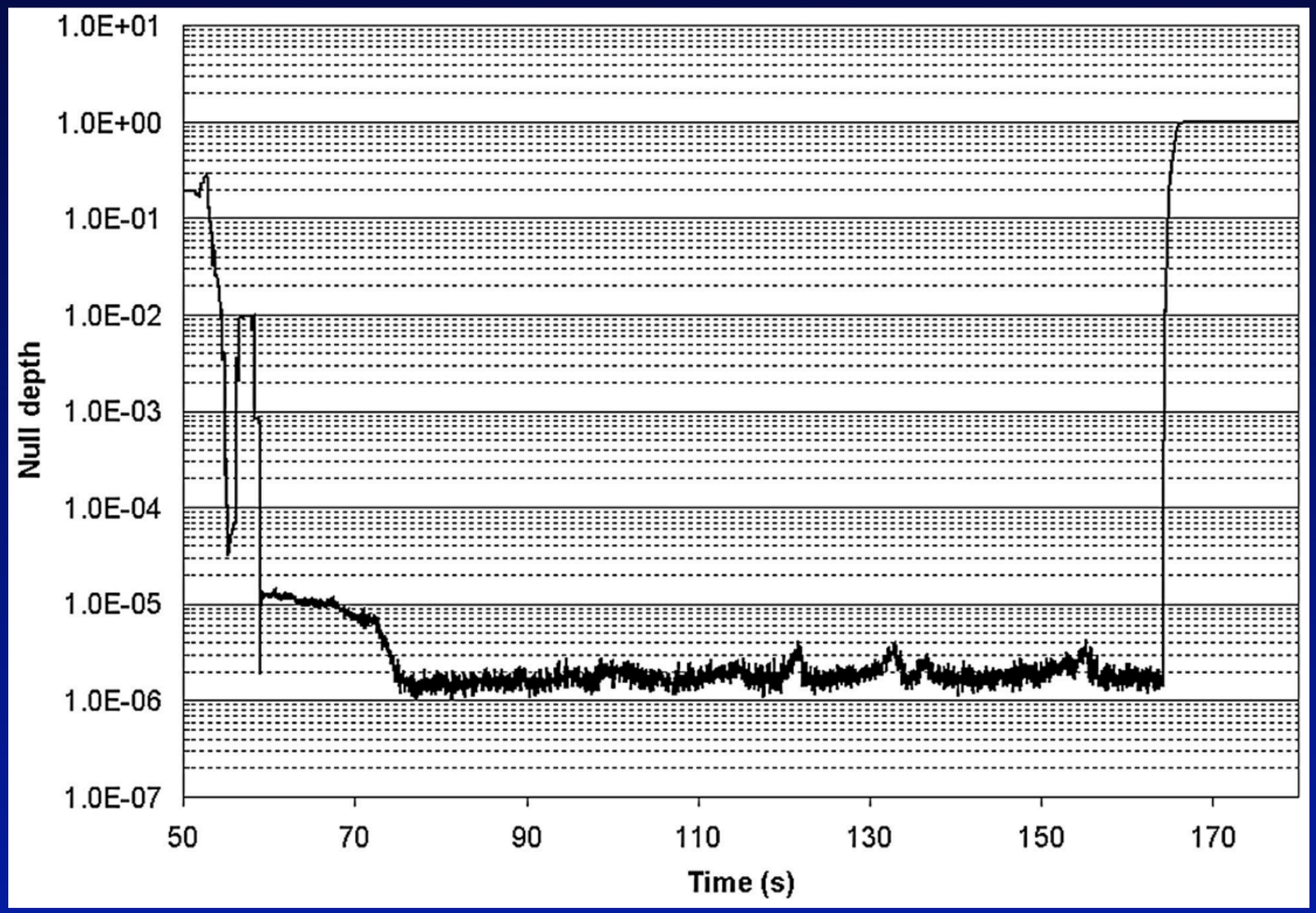


4.1. Visible nuller results

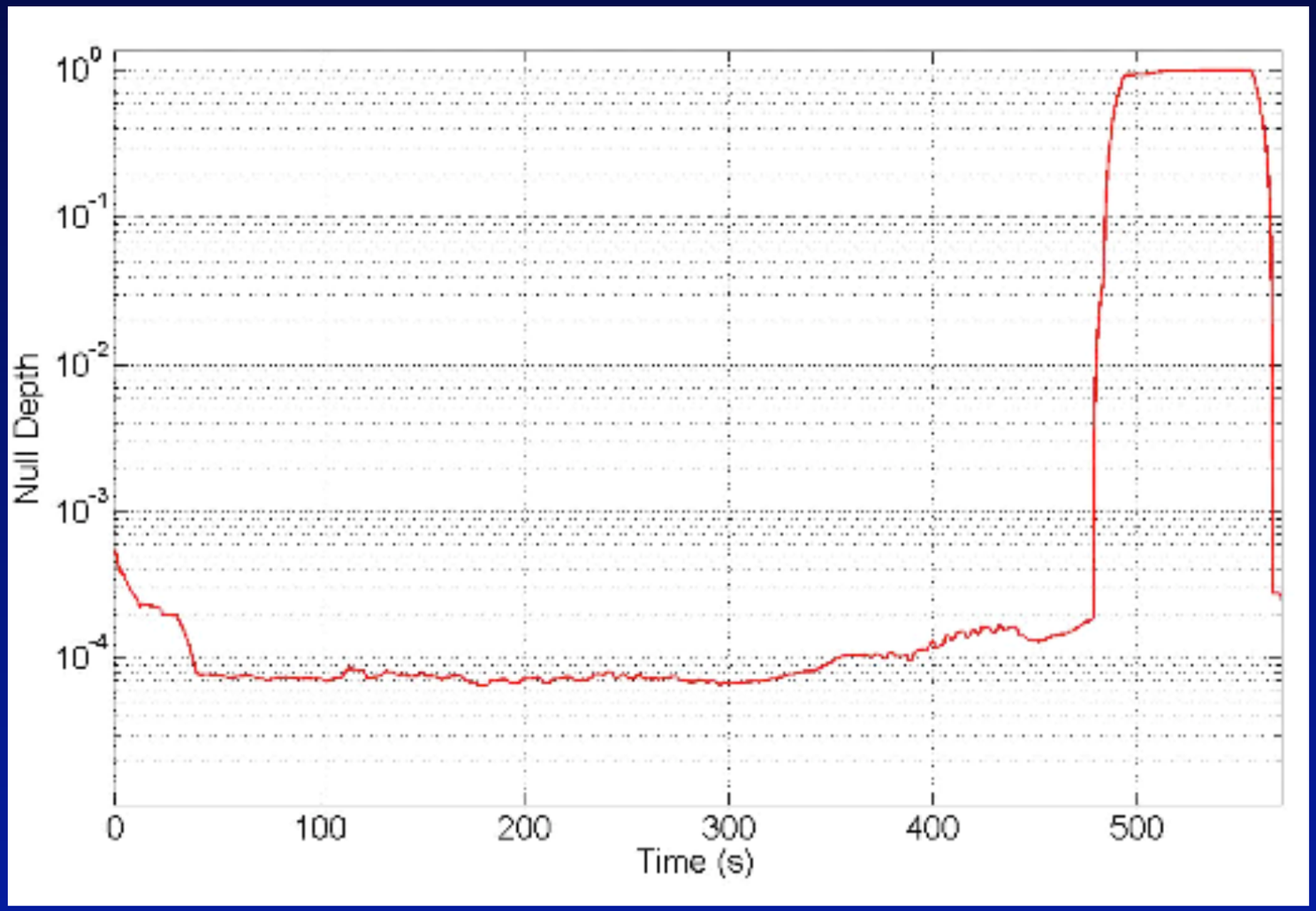
- Wavelength: monochromatic, 632.8 nm
- Best achieved null : 1.3×10^{-6} (770,000:1)



P. Haguenauer & E. Serabyn, Applied optics, April 2006

4.2. H-band nuller results

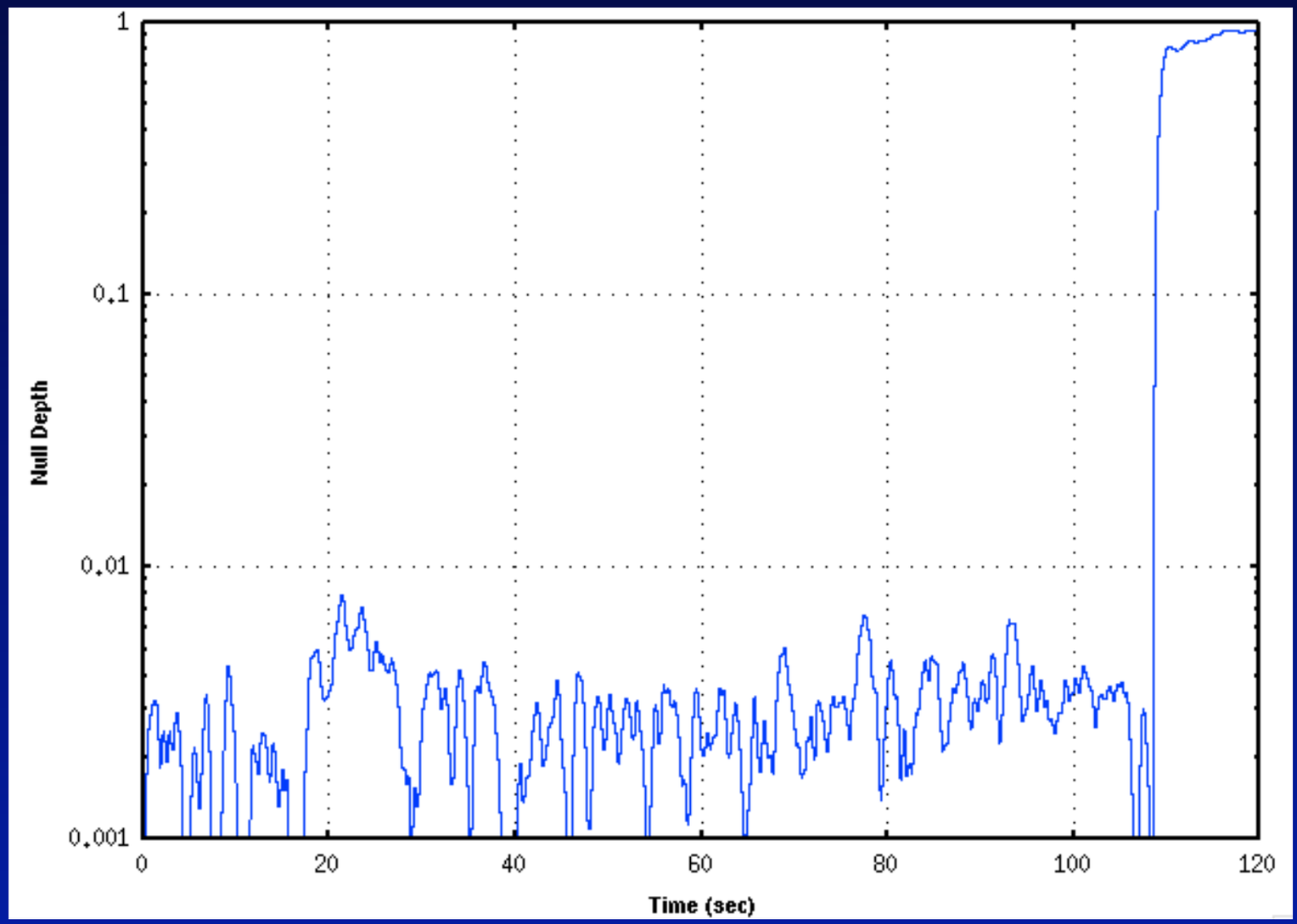
- Wavelength: H-band, 1.475-1.825 μm (20%)
- Best achieved null with APS: 7×10^{-5} (14,000:1)



S. Martin et al. , Proc. SPIE, 2008

4.3. K-band nuller lab results

- Best Null: 2×10^{-3} (500:1)
- Chromaticity limit: ~ 2×10^{-3} (500:1) ➡ OK for sky
- Amplitude mismatch: 5% ➡ ~2×10^{-4} (2000:1)



Result obtained in the nulling lab, May 2008

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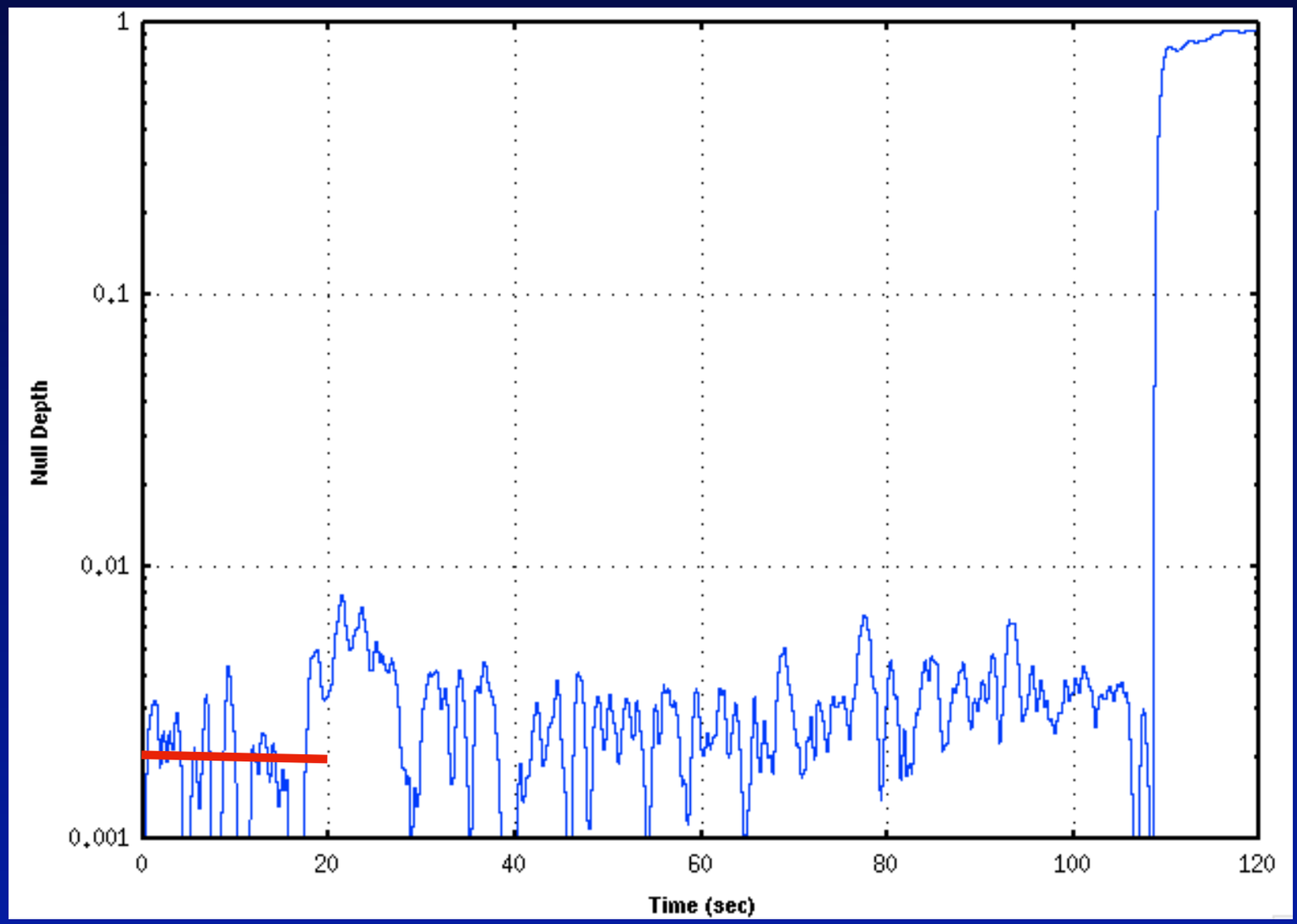

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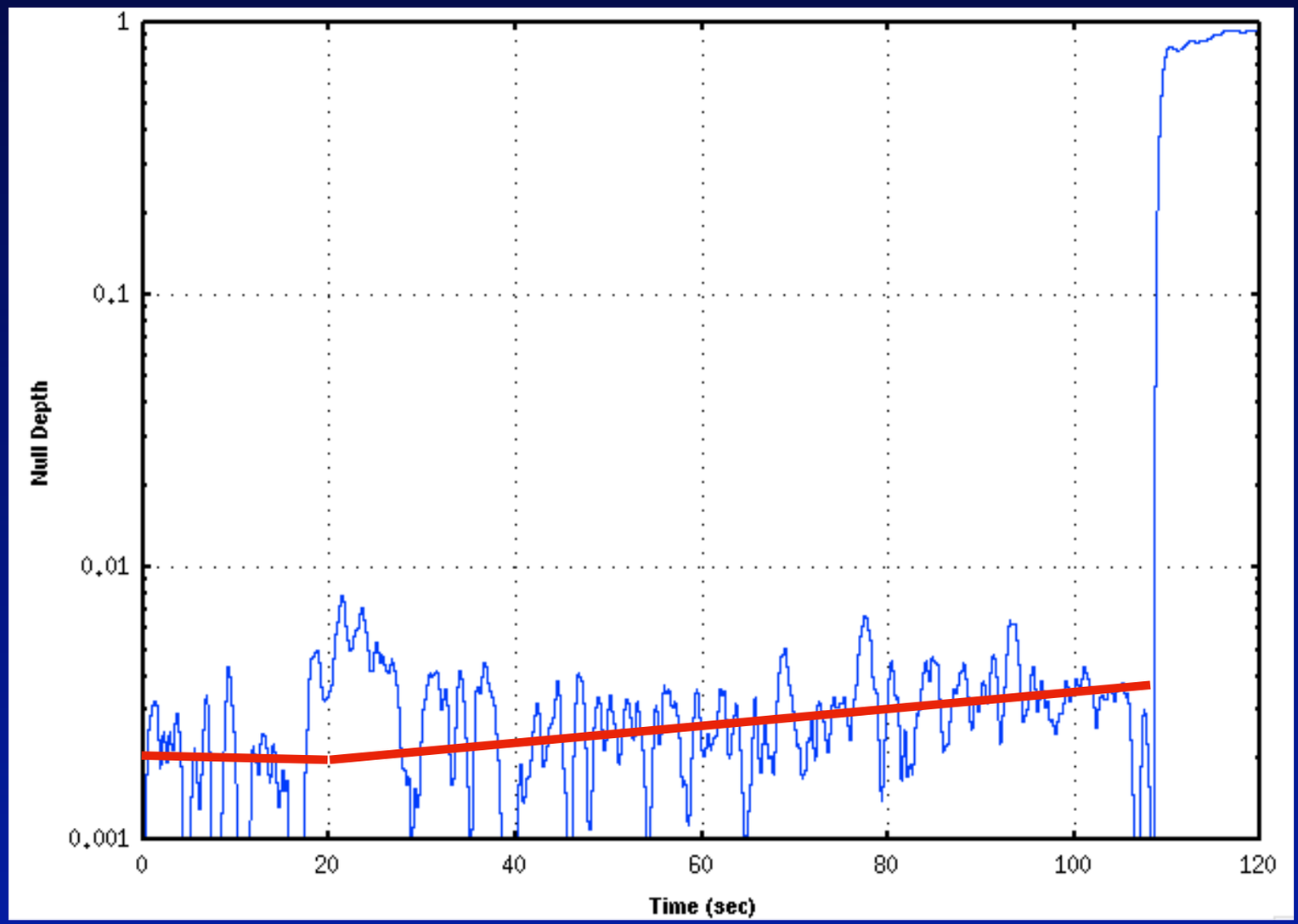
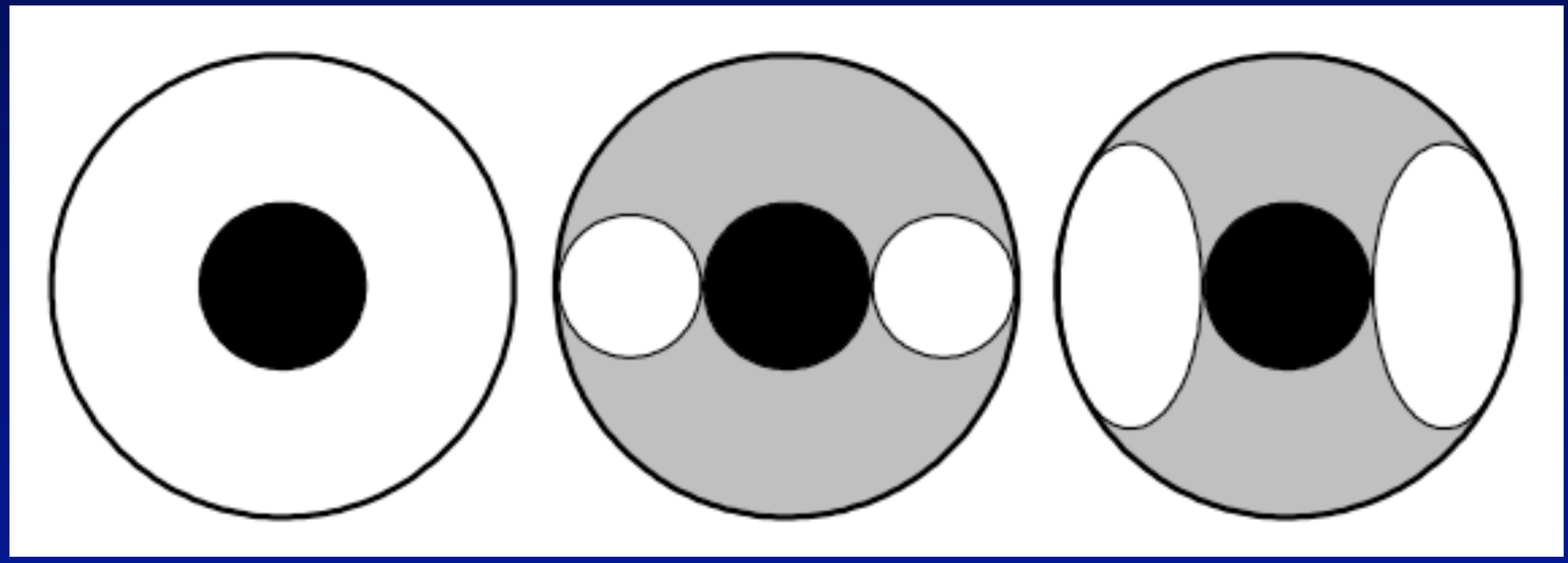


Result obtained in the nulling lab, May 2008

4.3. K-band nuller lab results

- Requirements on the pupil rotator:
  - Shear misalignment < 100 µm
  - Pointing misalignment < 100µrad



4.3. K-band nuller lab results

- Requirements on the pupil rotator:
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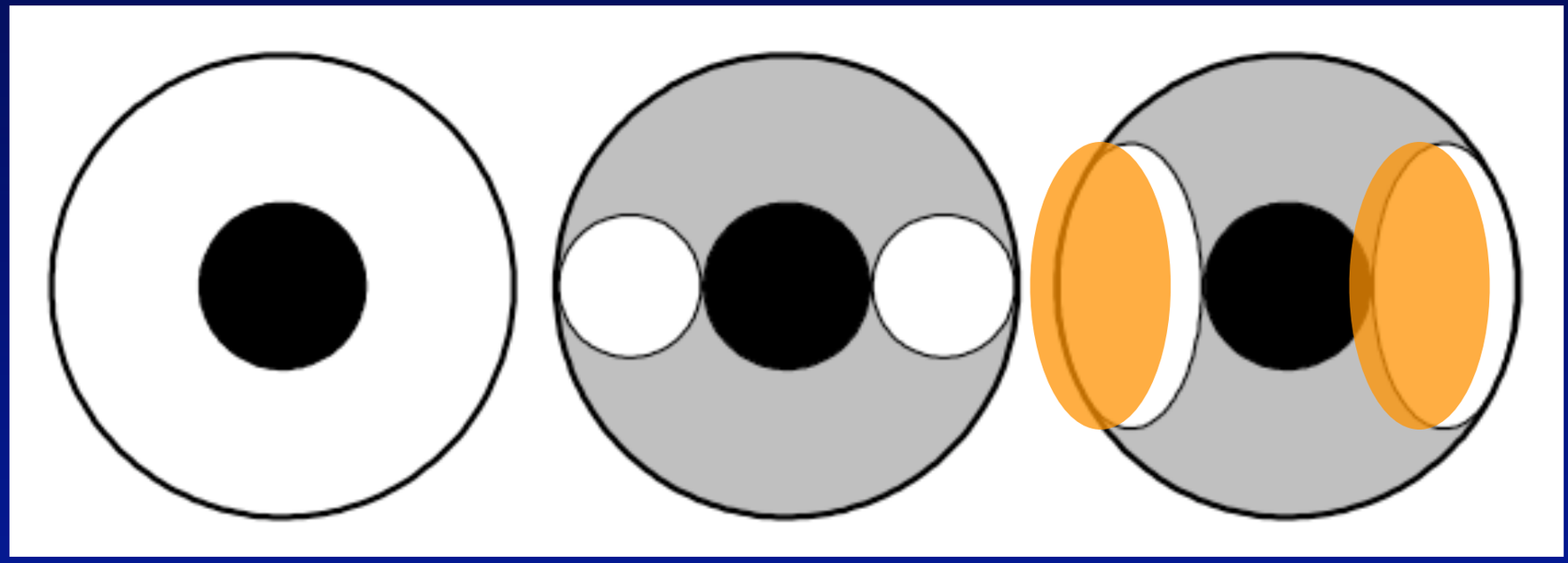
  - Pointing misalignment < 100µrad



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- Requirements on the pupil rotator:
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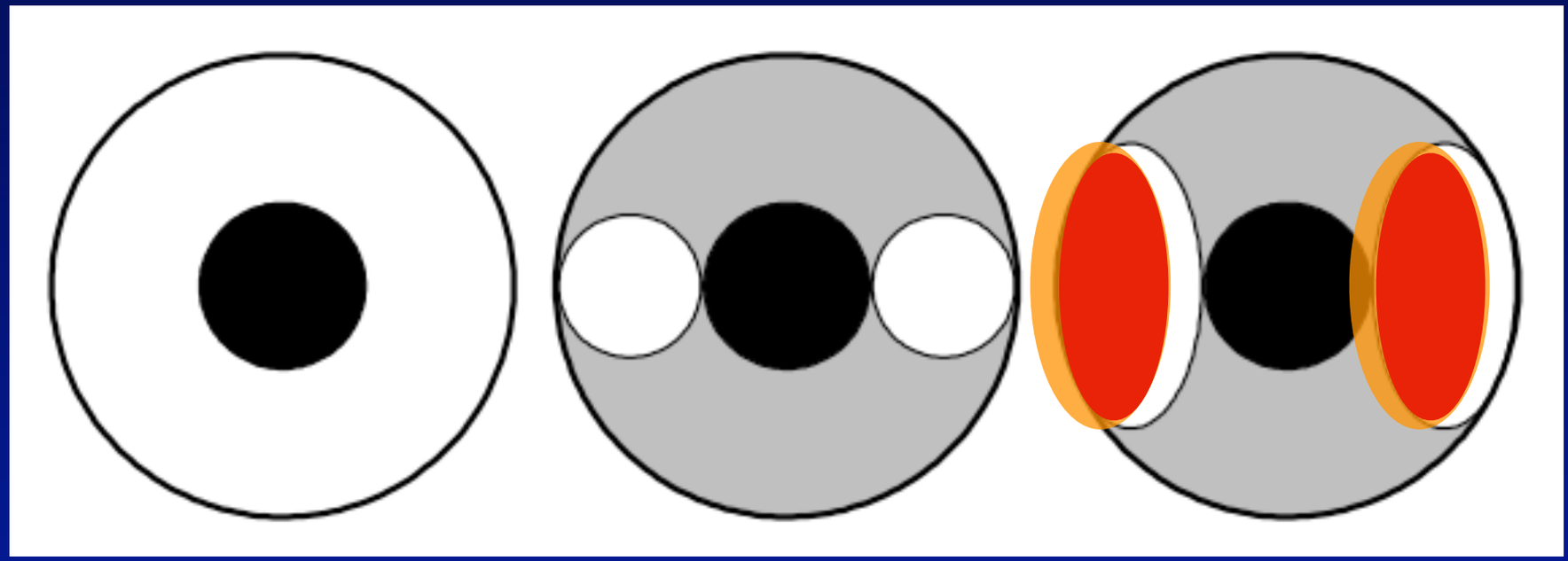
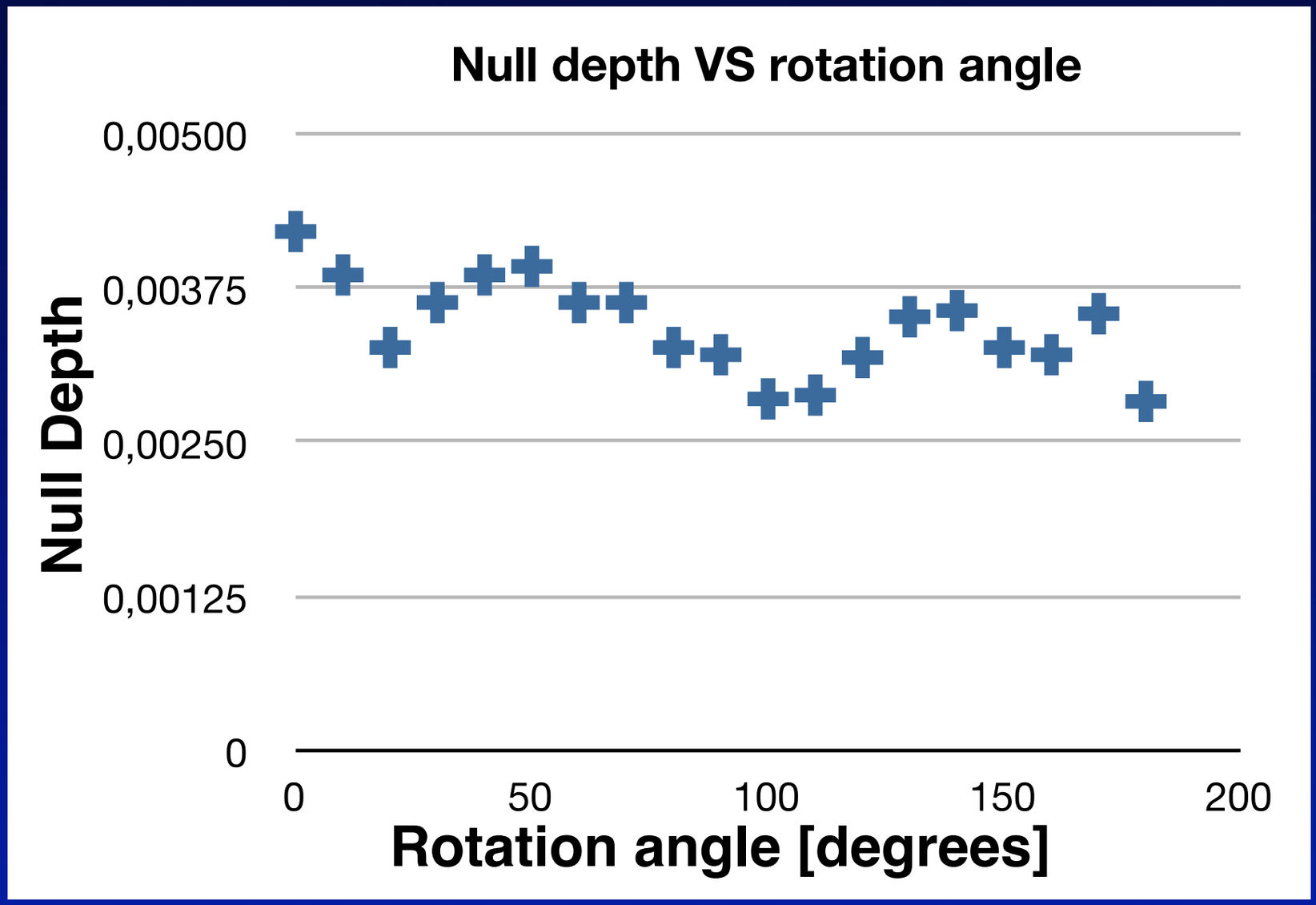


4.3. K-band nuller lab results

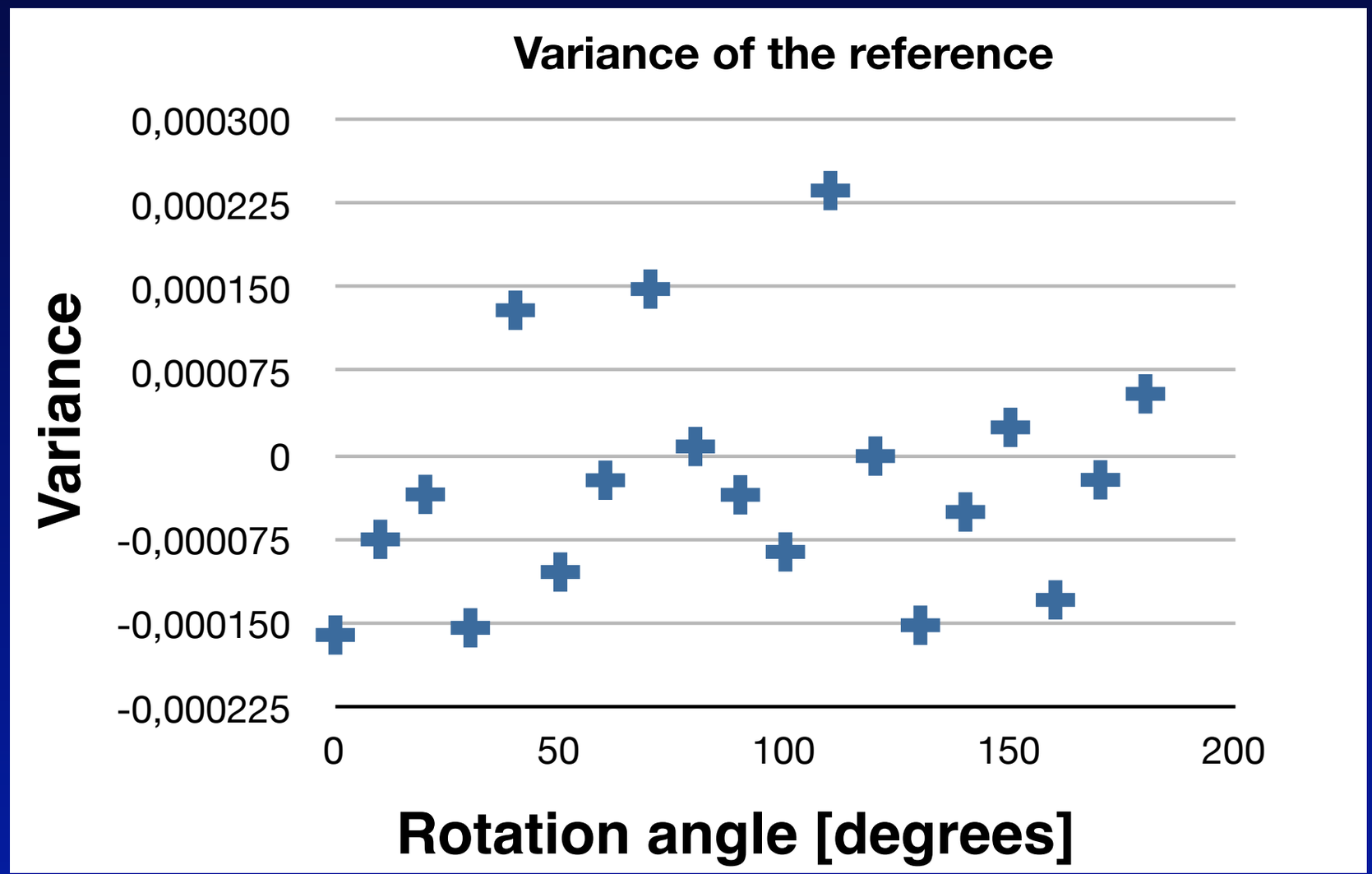
- Stability of the null when rotating
  - ➡Null depth vary between 2.7×10^{-3} - 4×10^{-3}



Result obtained in the nulling lab, September 2008

4.3. K-band nuller lab results

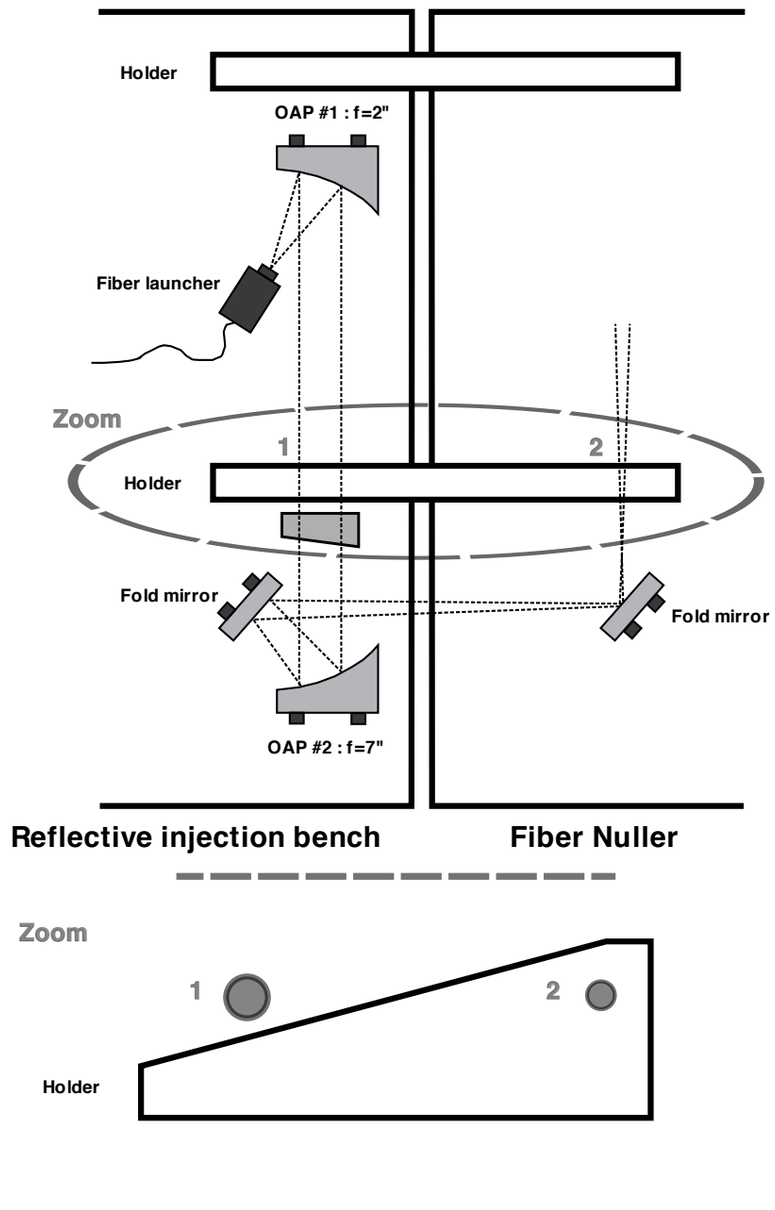
- What about the stability between 2 ≠rotations?
  - ➡Stability between measurements > 2.3×10^{-4}
  - ➡Stability measured over a couple of hours



Result obtained in the nulling lab, September 2008

4.3. K-band nuller lab results

- Detection of a faint companion
- Companion characteristics:
  - Wedge angle ≈ 15”
  - Similar to 40 mas on the sky
  - Wedge made of CaF2
  - $\Delta I=[(n_1-n_2)^2/(n_1+n_2)^2]^2=8x10^{-4}$



4.3. K-band nuller lab results

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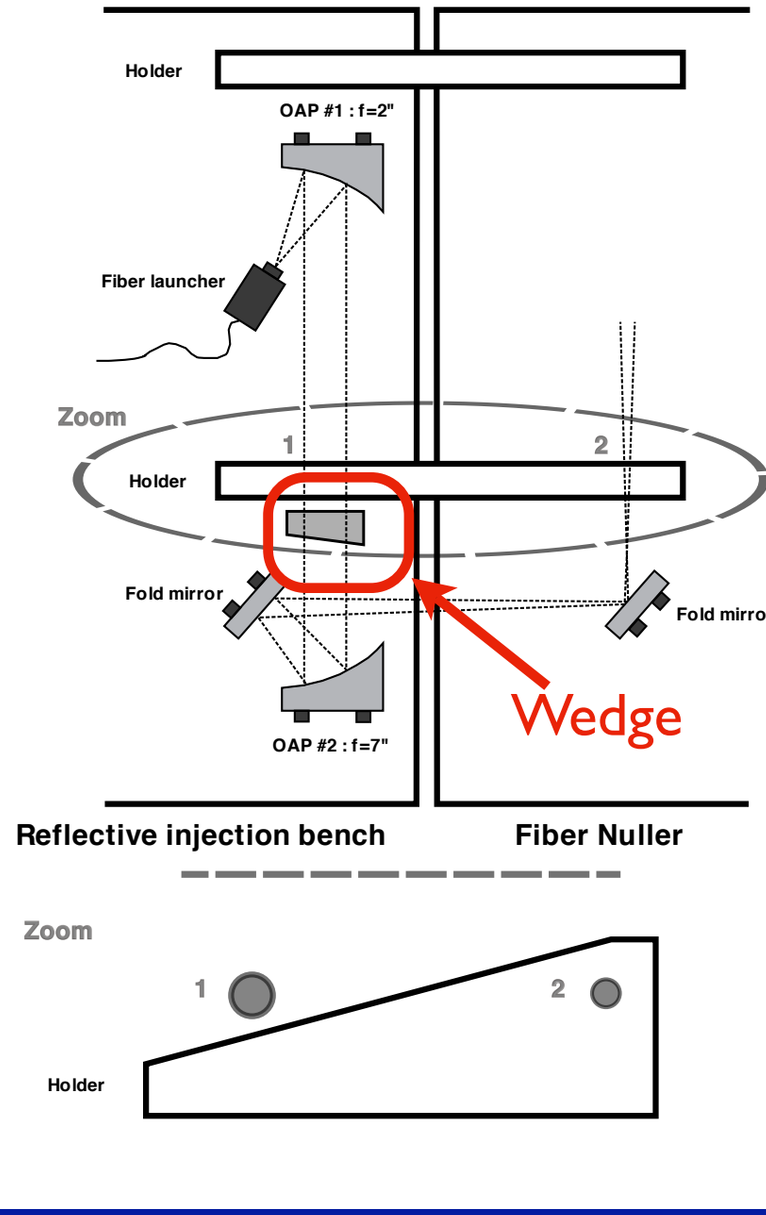
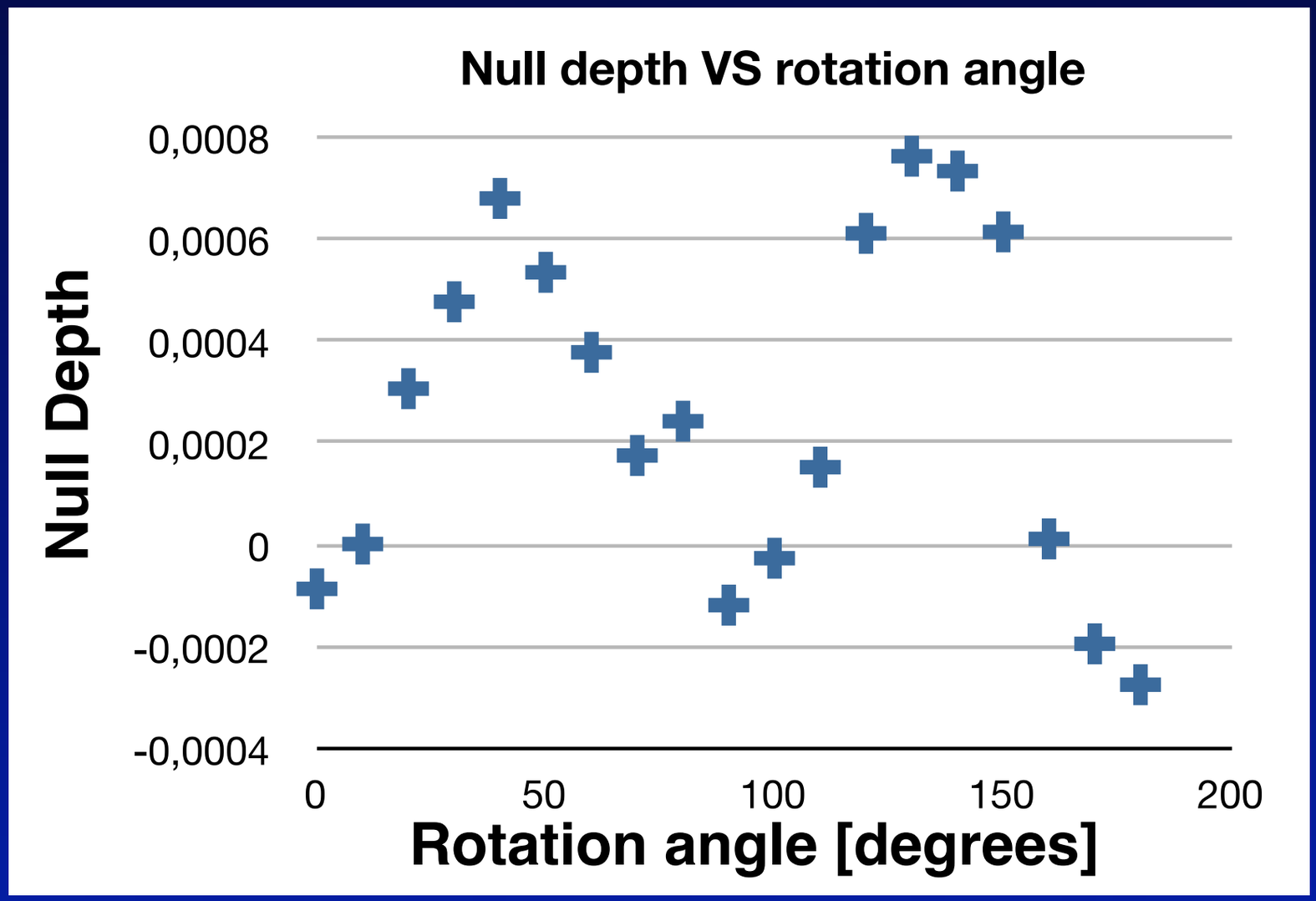


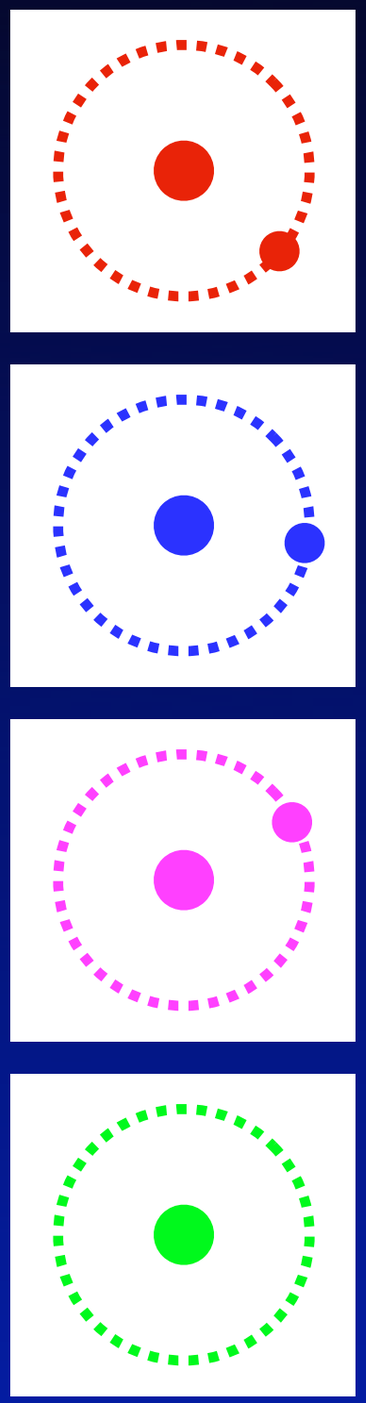
4.3. K-band nuller lab results

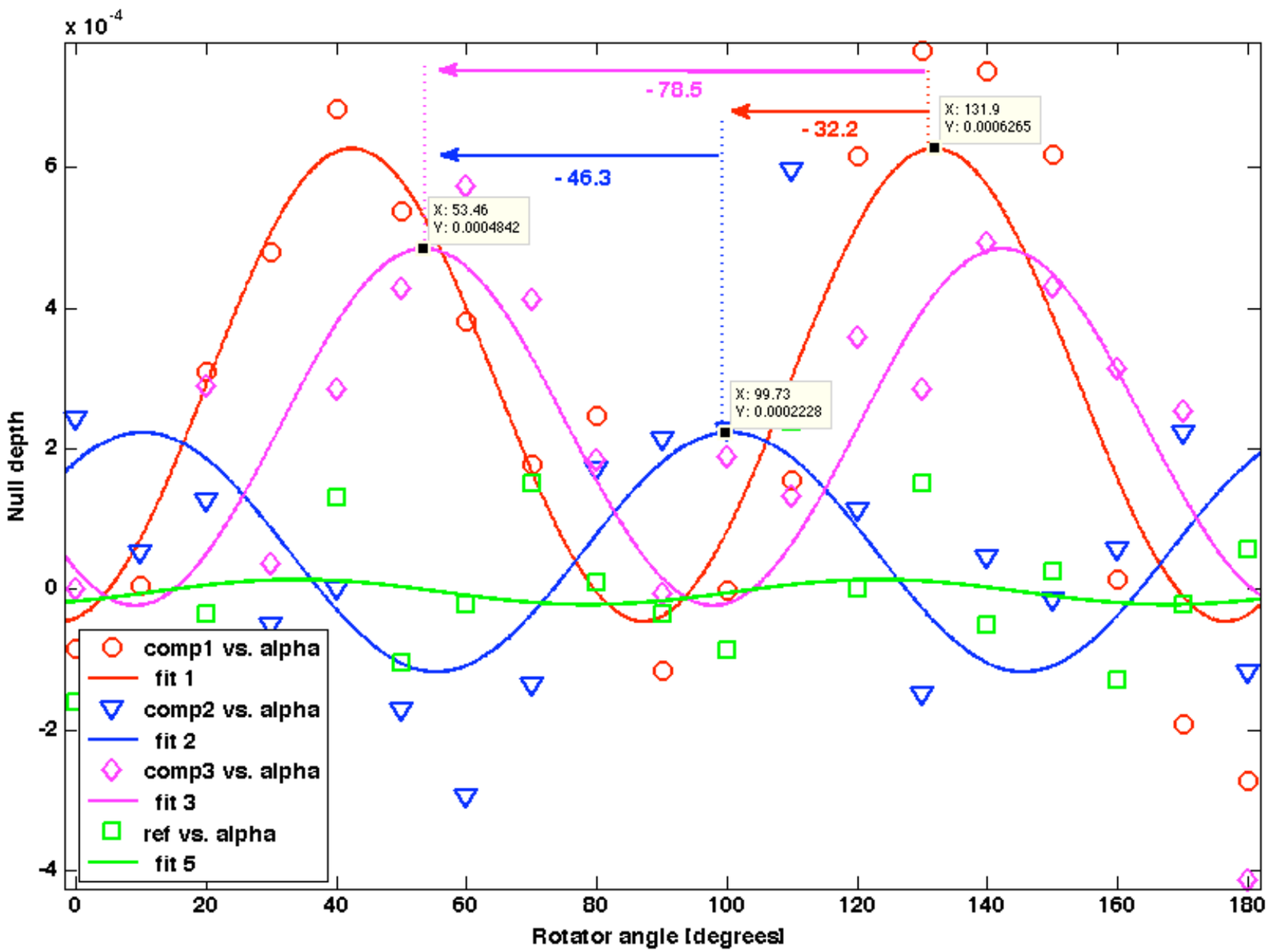
- Significant oscillations detected (6-8σ)
- Separation between the 2 peaks = 90°
- Max of oscillations consistant with ΔI_{comp}



Result obtained in the nulling lab, September 2008

4.3. K-band nuller lab results

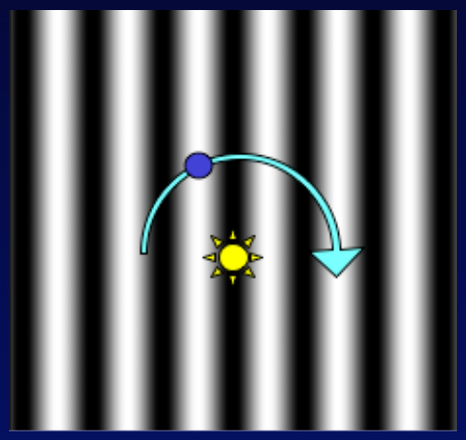




Results obtained in the Nulling lab with CaF2 wedged plate, July 2008

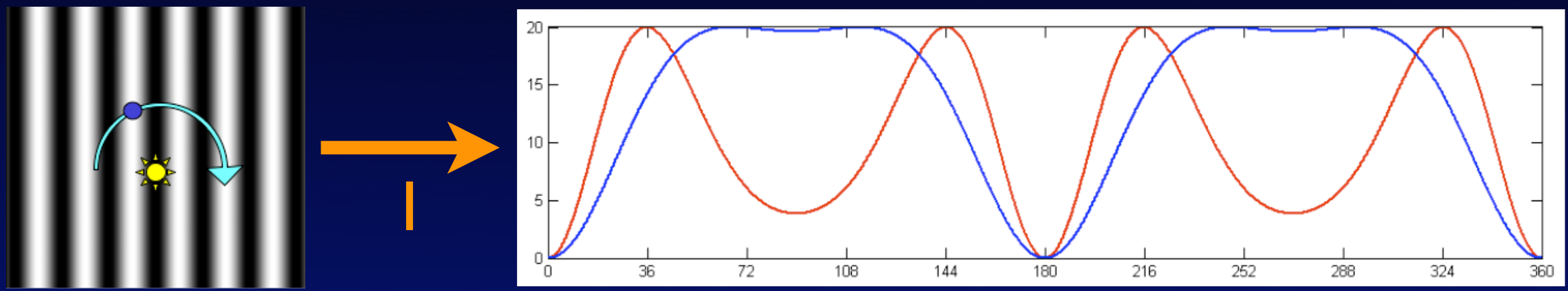
4.3. K-band nuller lab results

Maximum Correlation Method



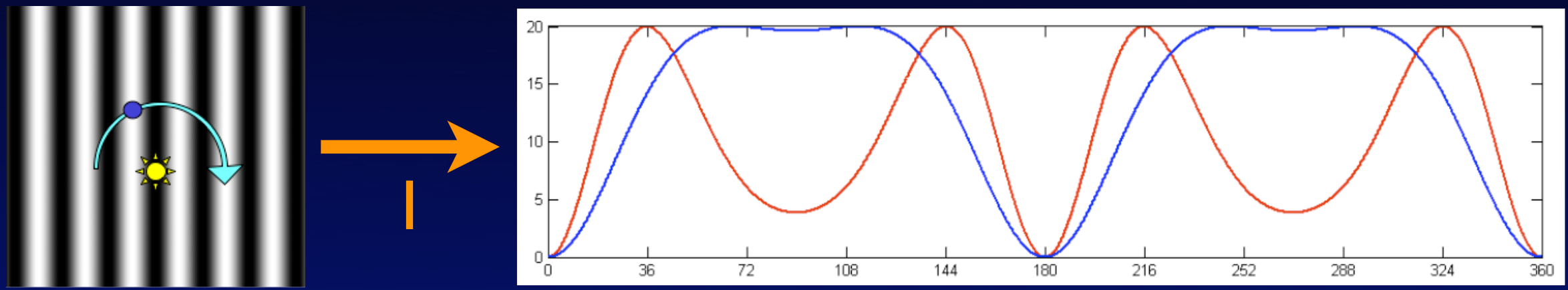
4.3. K-band nuller lab results

Maximum Correlation Method



4.3. K-band nuller lab results

Maximum Correlation Method

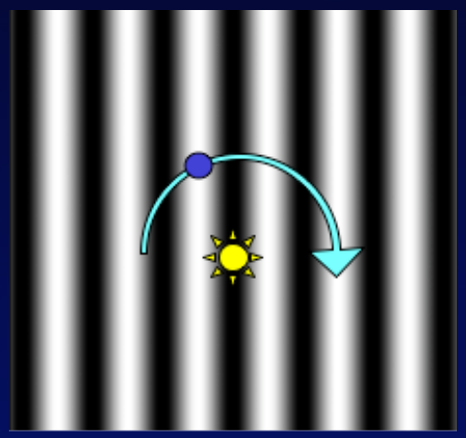


2

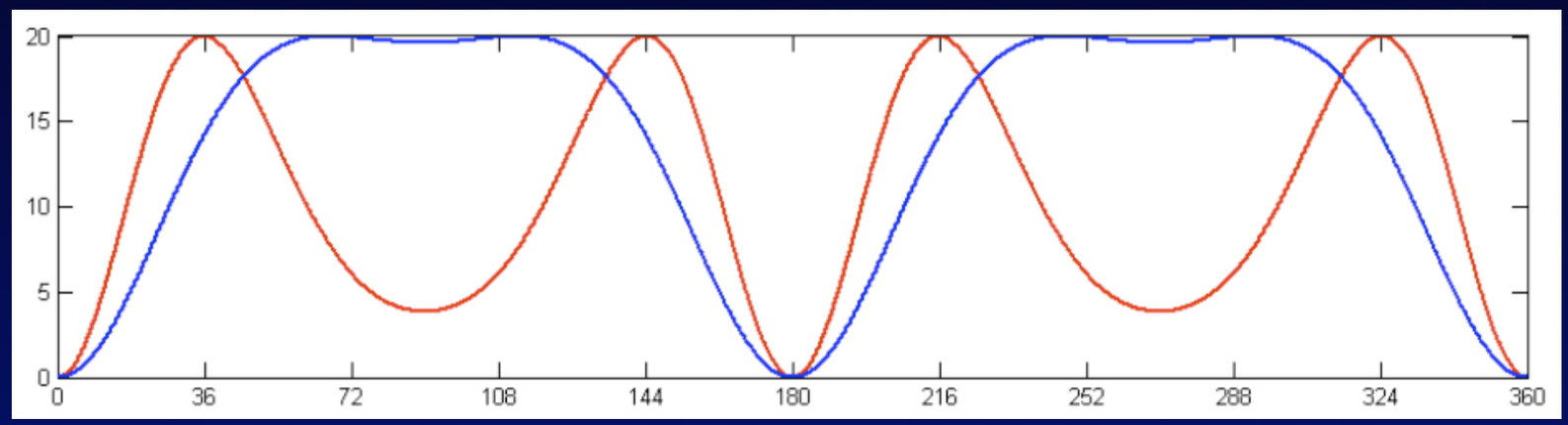
$$\Phi(R,\theta) = \frac{\sum S(t) * T(R,\theta,t)}{\sqrt{\sum T(R,\theta,t) * T(R,\theta,t)}}$$

4.3. K-band nuller lab results

Maximum Correlation Method



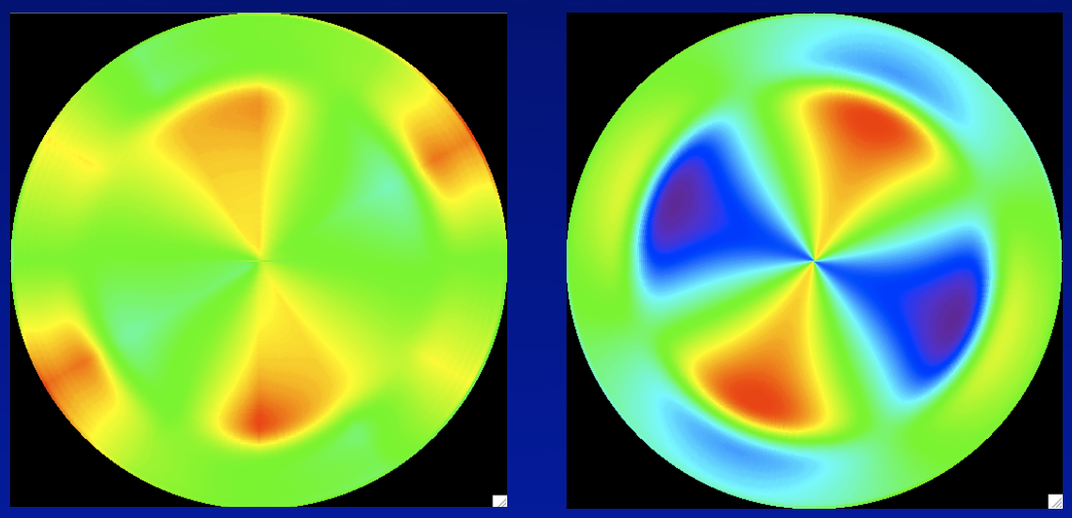
1



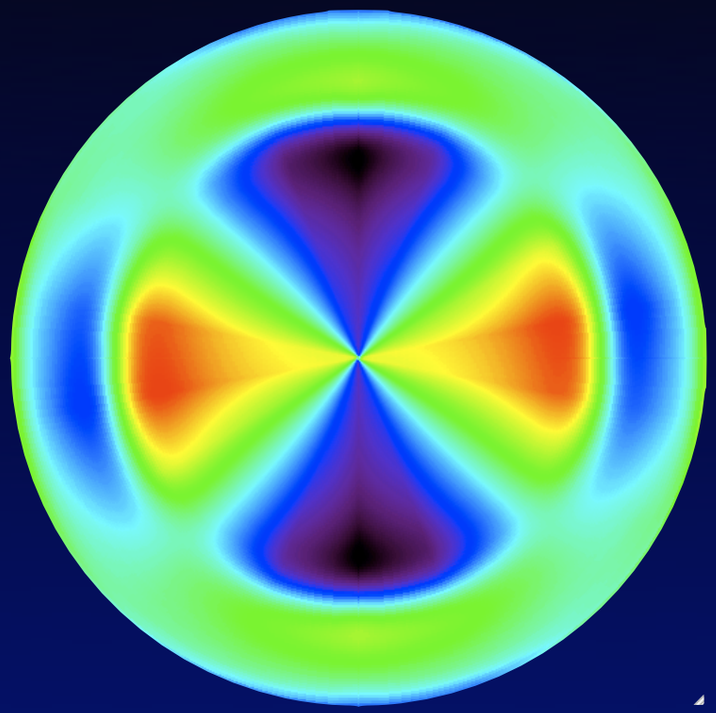
2

$$\Phi(R,\theta) = \frac{\sum S(t) * T(R,\theta,t)}{\sqrt{\sum T(R,\theta,t) * T(R,\theta,t)}}$$

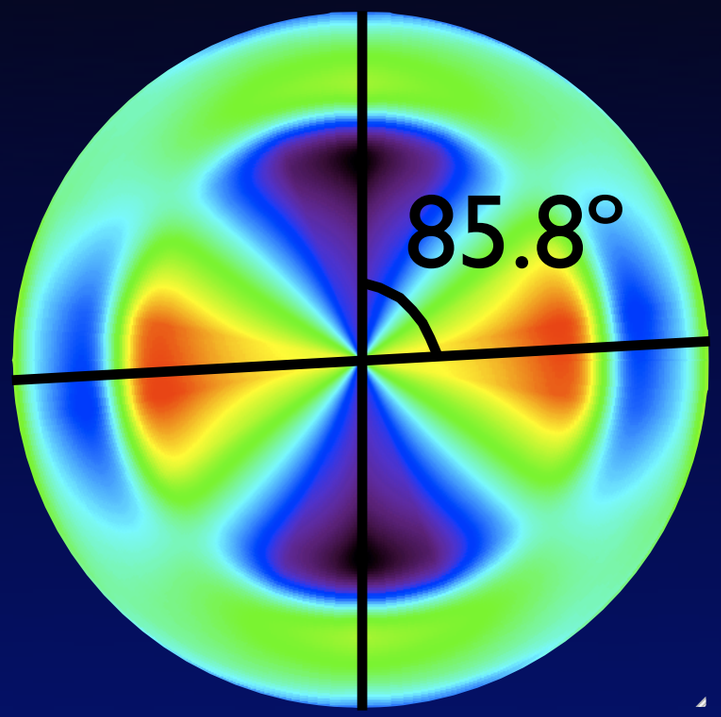
3



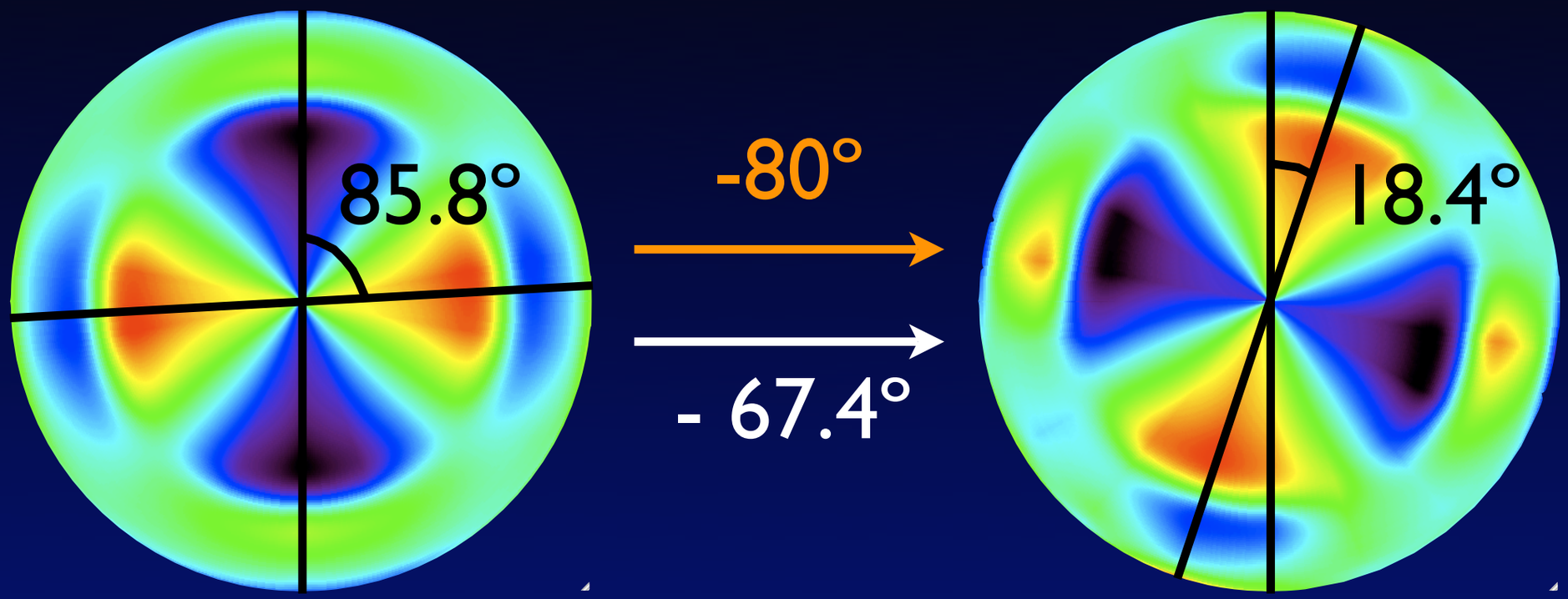
4.3. K-band nuller lab results



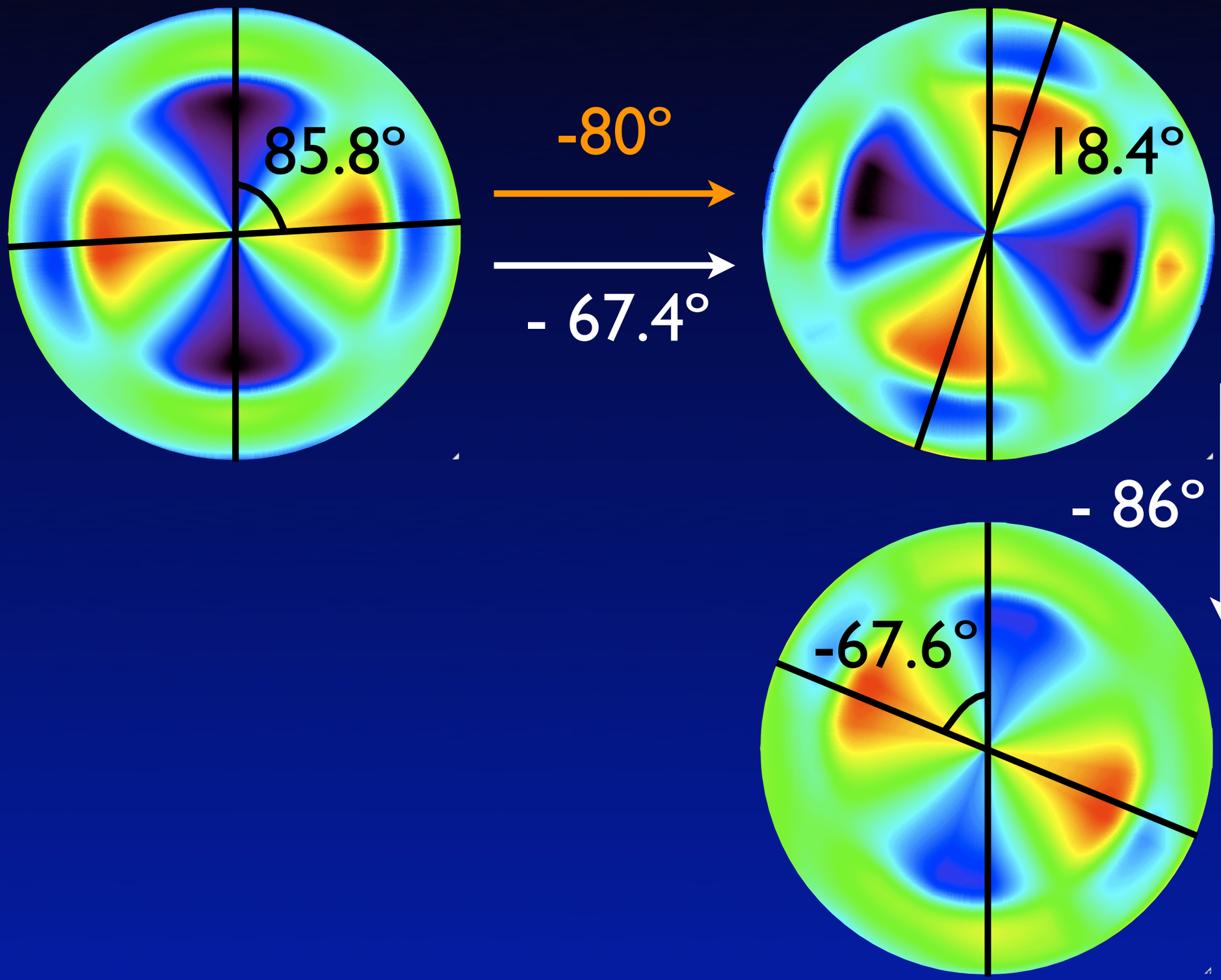
4.3. K-band nuller lab results



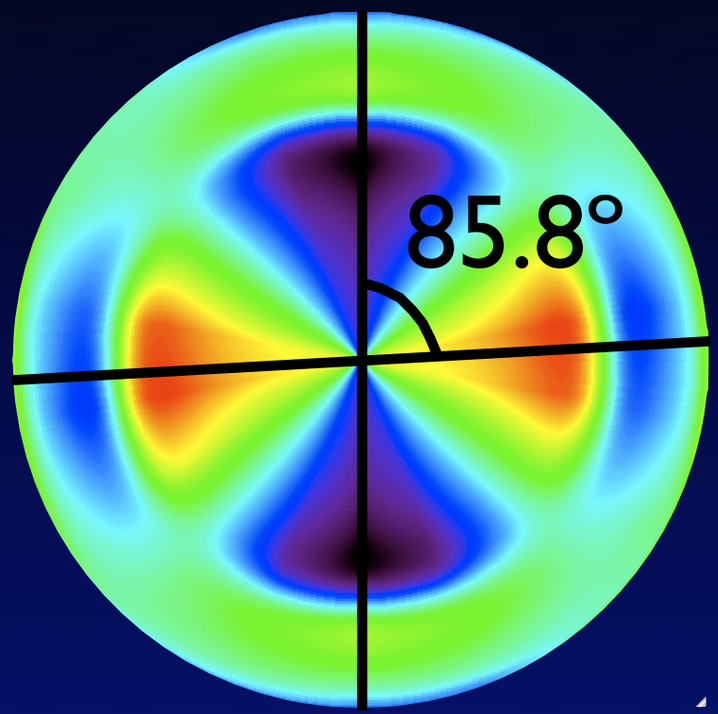
4.3. K-band nuller lab results



4.3. K-band nuller lab results

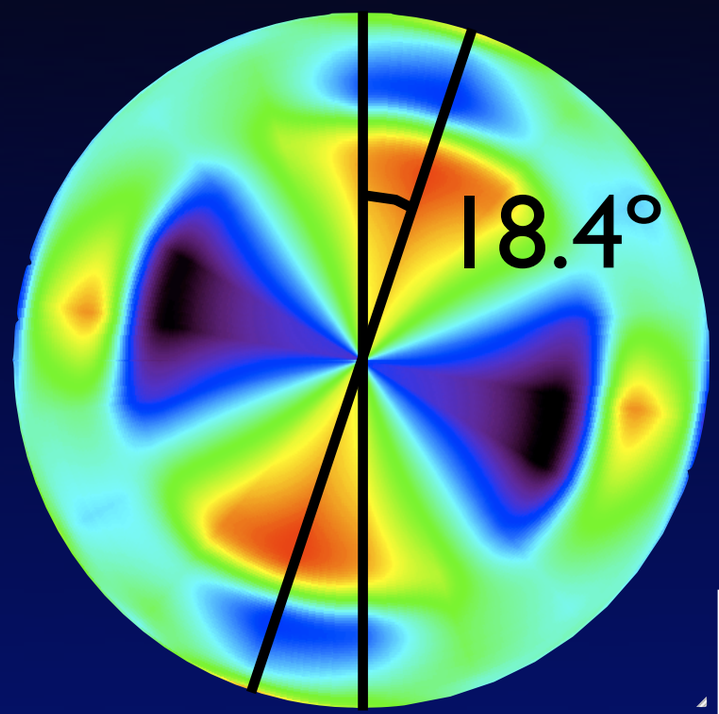


4.3. K-band nuller lab results



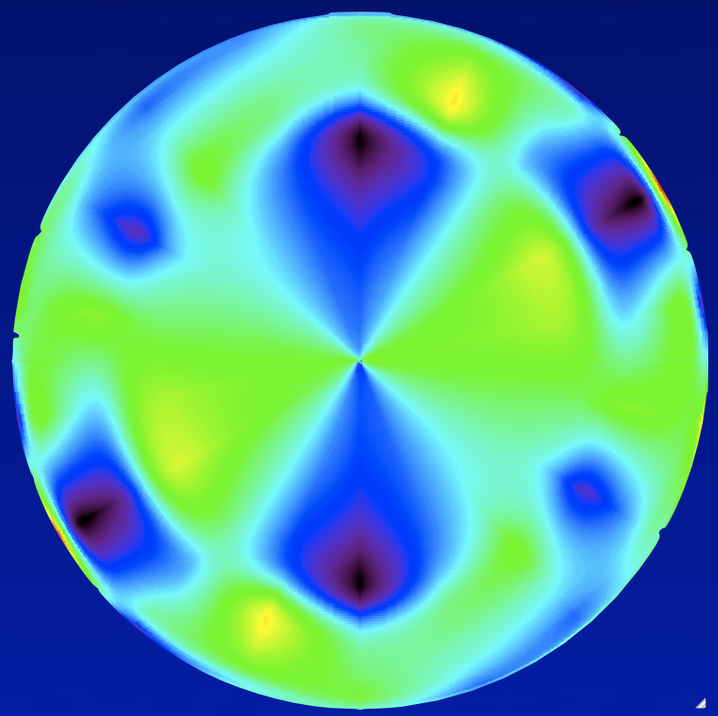
-80°

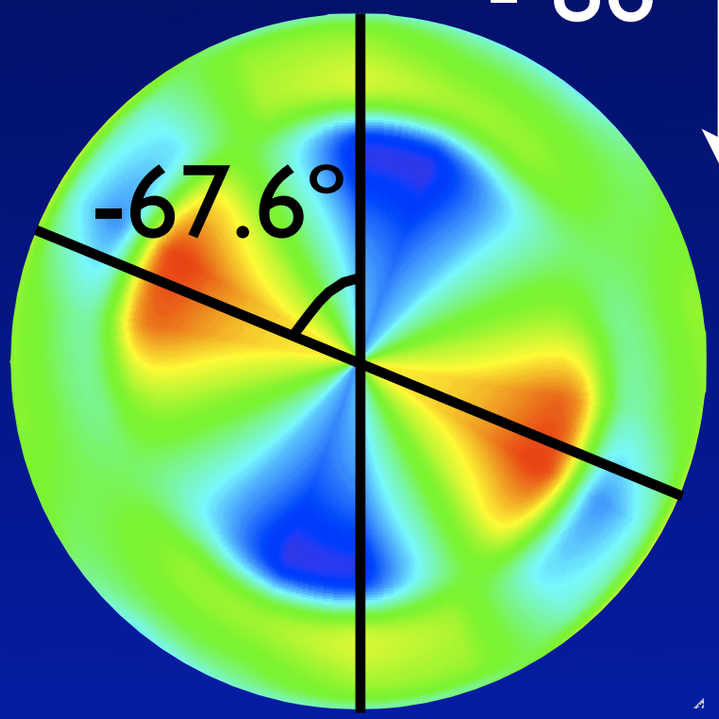
- 67.4°



- 86°

-80°





4.3. K-band nuller lab results

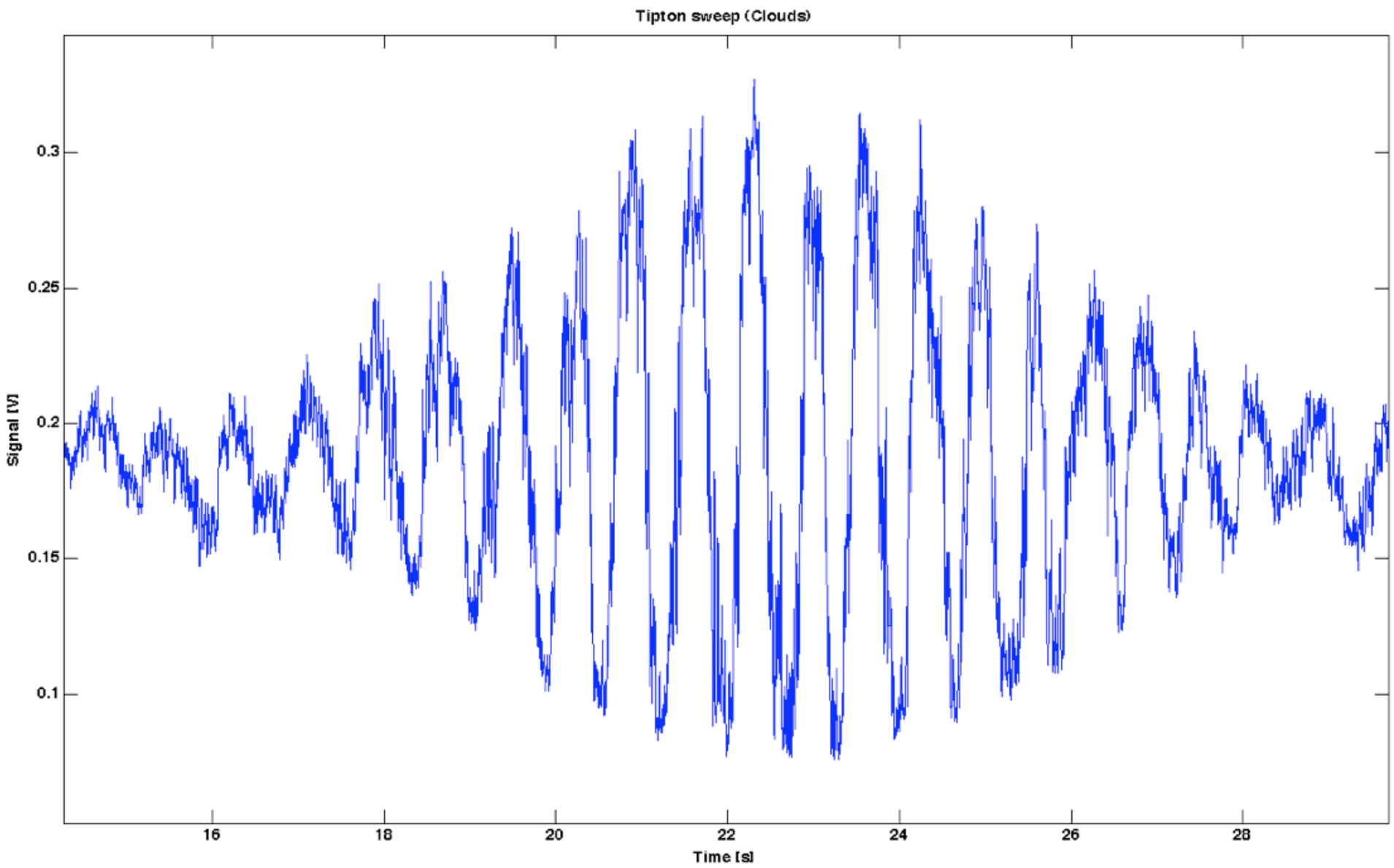
	Theory	Sine fitting	MCM
Pos1-Pos2	-40	-32.2	-33.7
Pos2-Pos3	-40	-46.3	-43
Pos1-Pos3	-80	-78.5	-76.7

5.Results on the sky

- Fiber Nuller run (July 2008)
- Objective #1: Measuring stellar diameters
- Objective #2: Observing a low contrast binary system

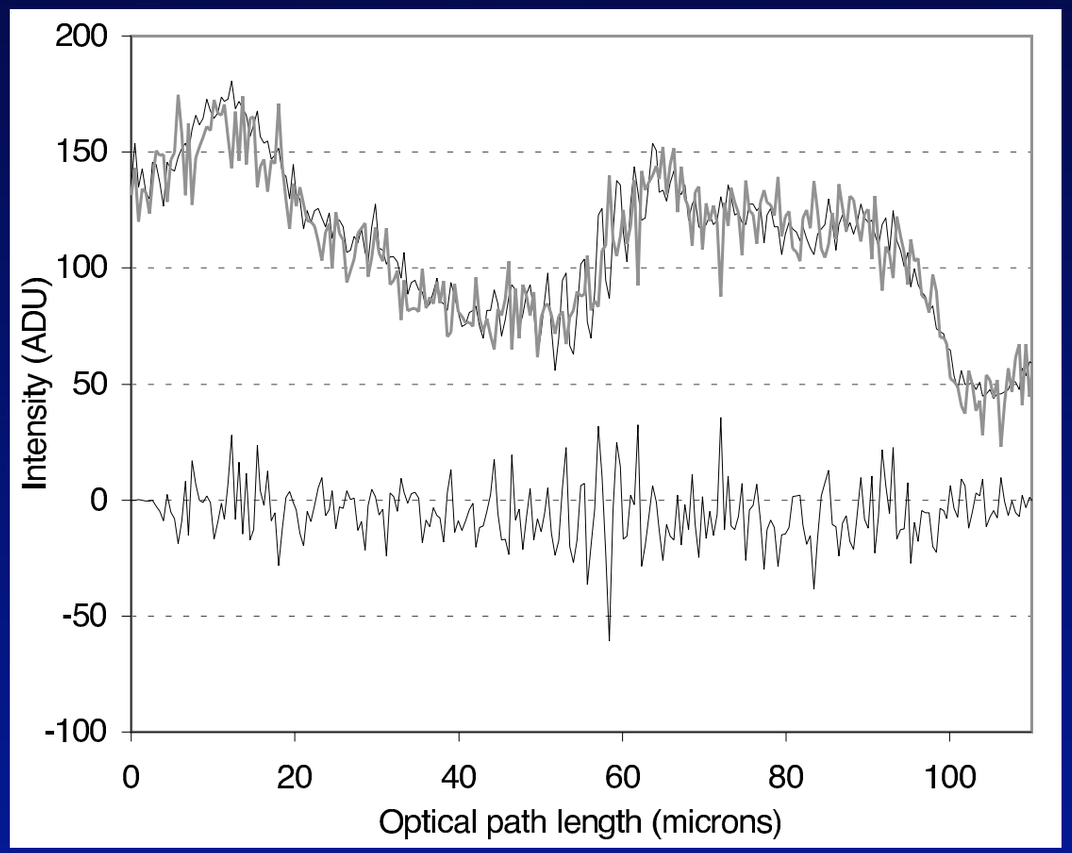
5.Results on the sky

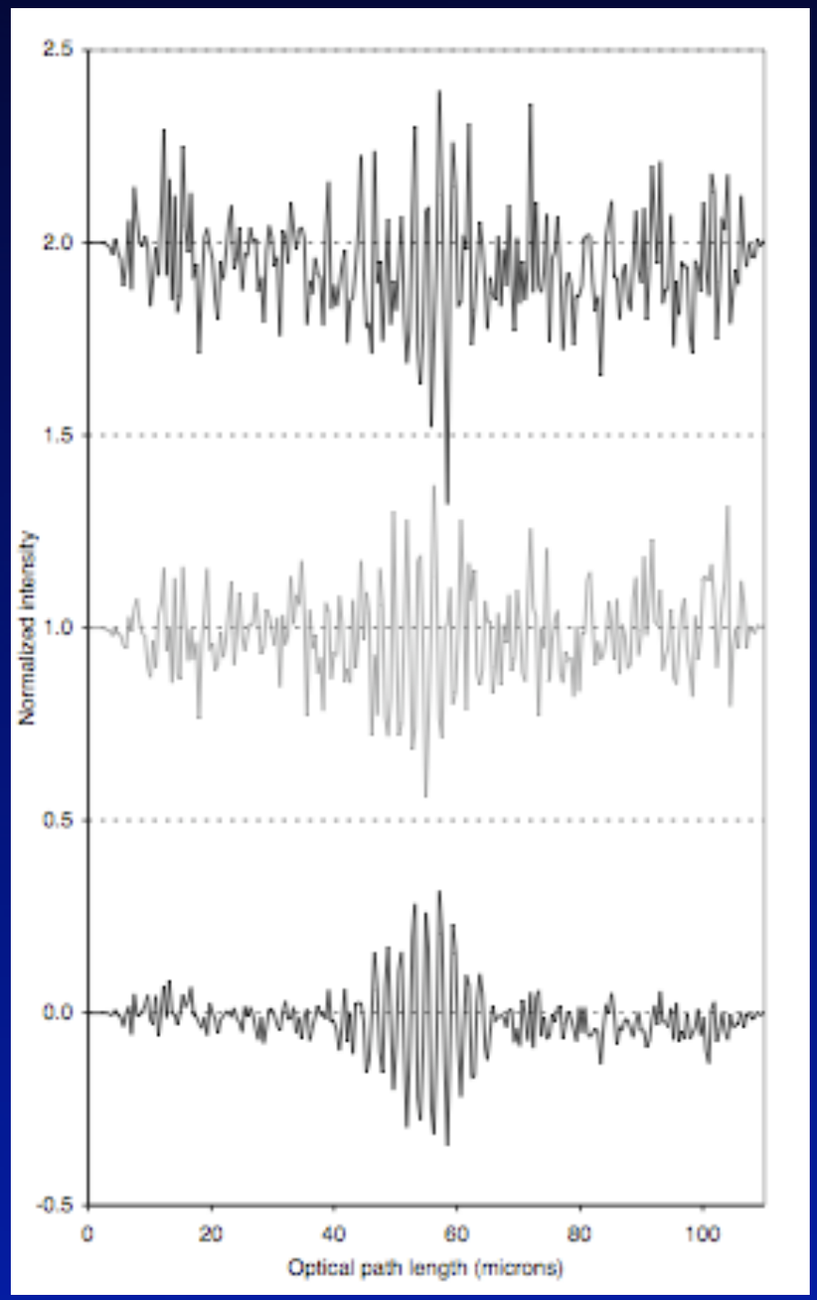
- First Fringe on Gamma Draconis



5.Results on the sky

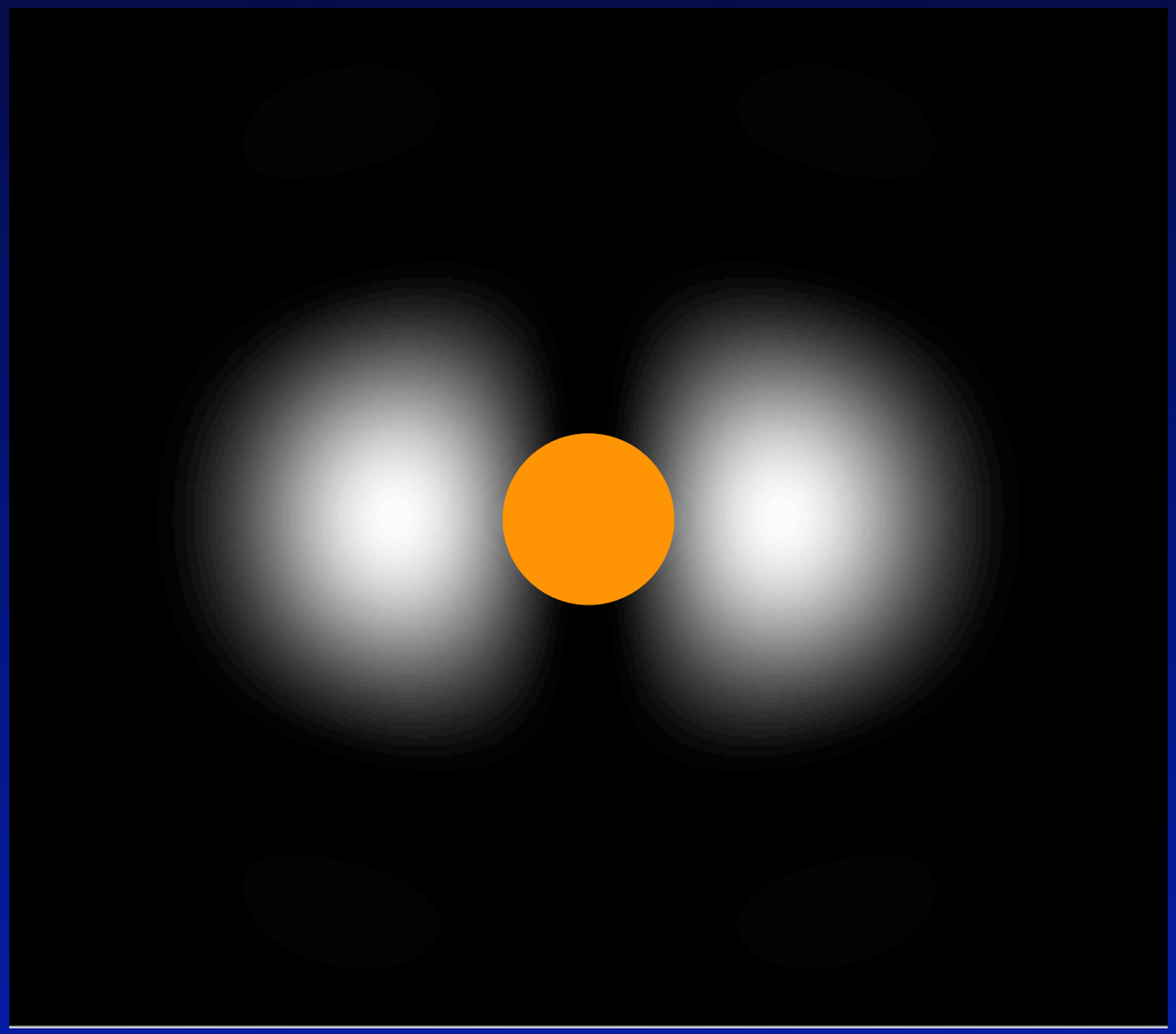
- Comparison with fringes of long baseline interferometers



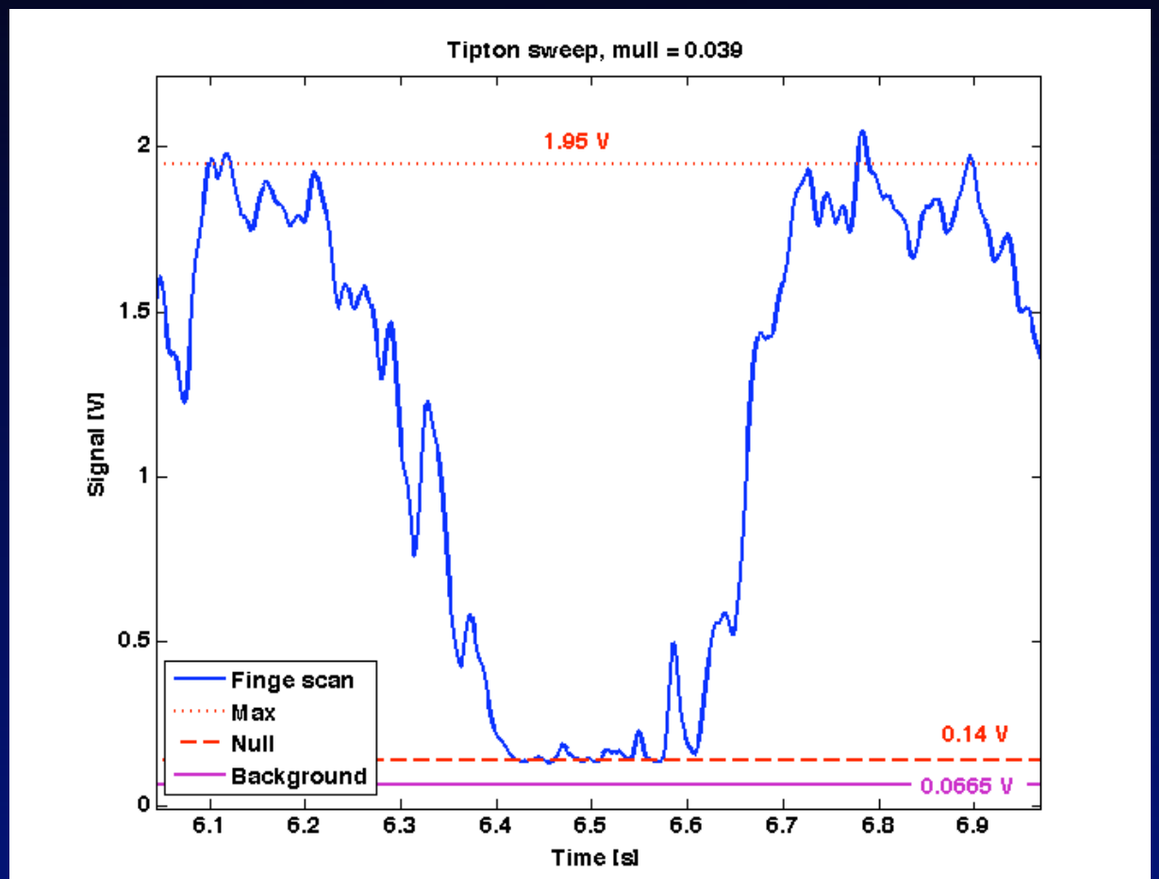


5.Results on the sky

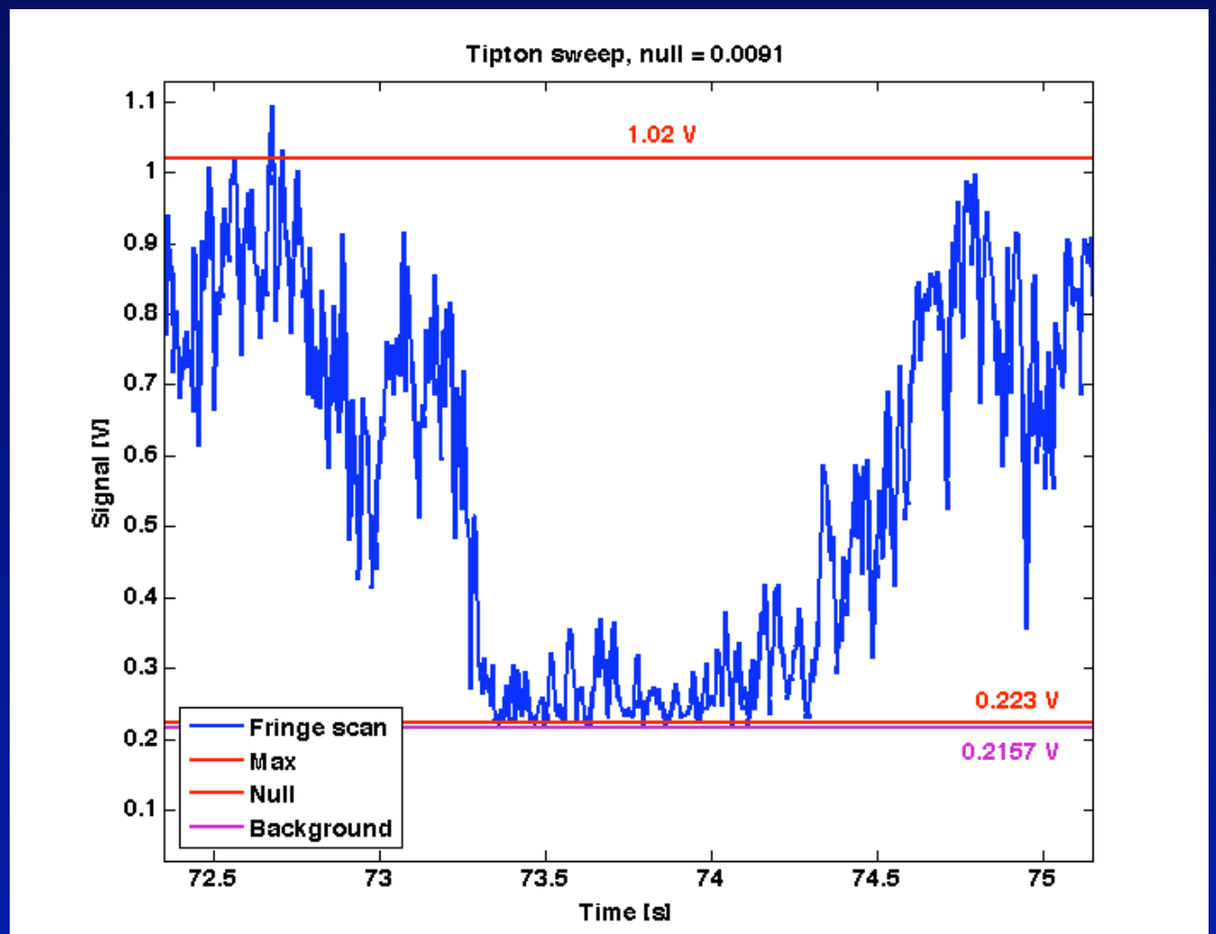
- Measuring stellar diameter with a nuller
  - Leakage = $\pi\theta^2B^2/\lambda^2$



5.Results on the sky



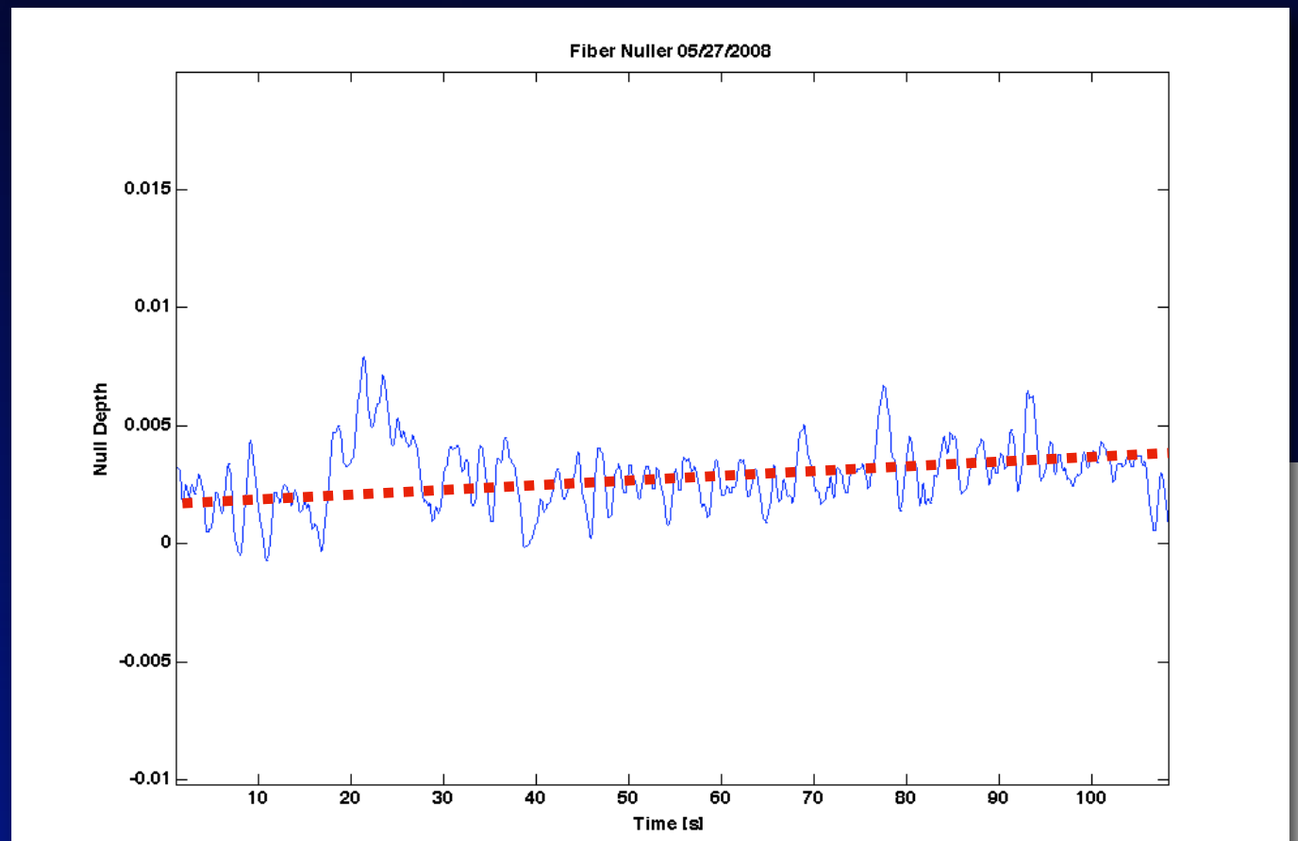
- Alpha Herculis
- Diameter = 32 mas
- Null depth: 3.86×10^{-2}



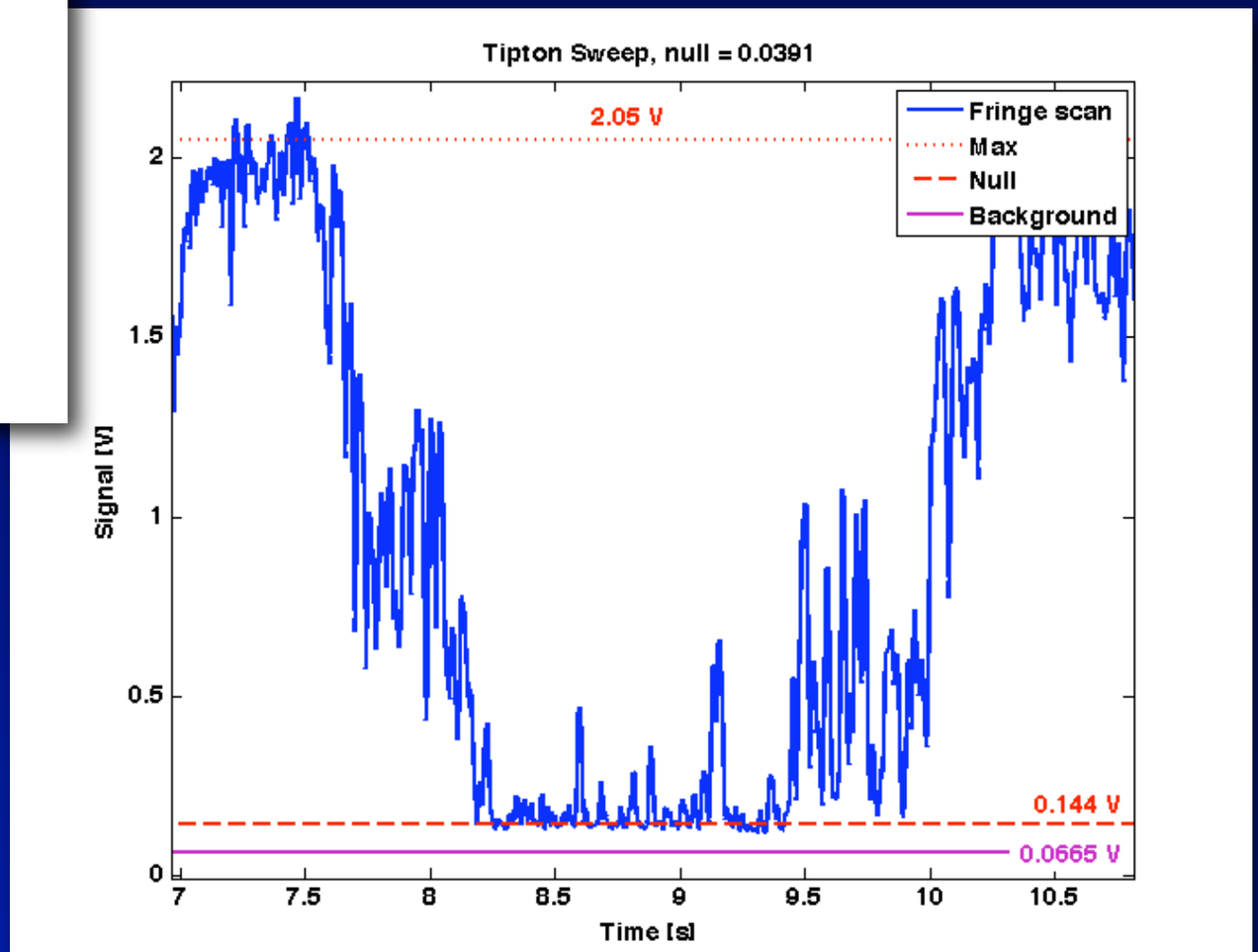
- Gamma Draconis
- Diameter = 10.9 mas
- Null depth: 4.7×10^{-3}

5.Results on the sky

- Measuring a null limited by the observed object



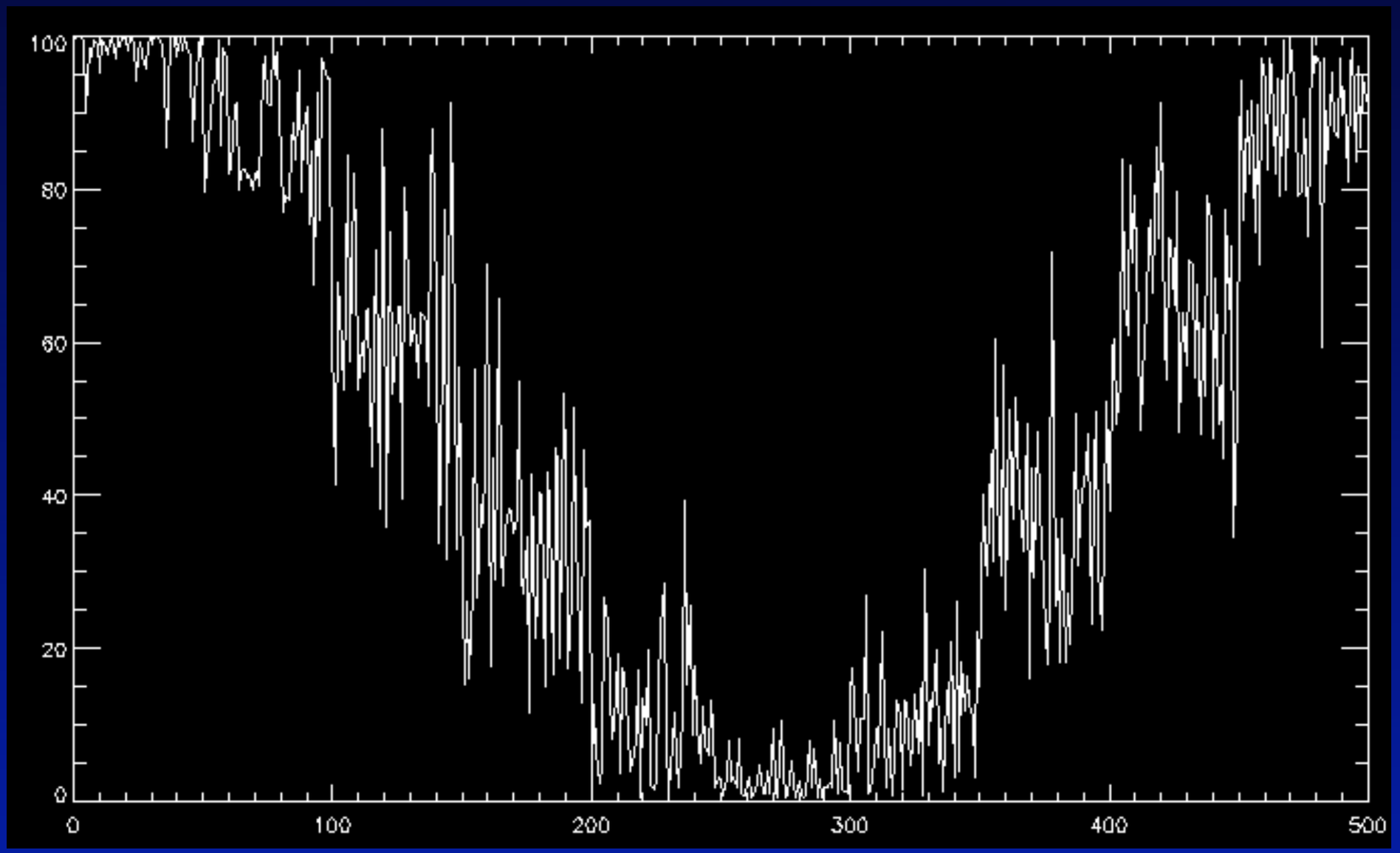
White noise around the null



The noise only increases the leakage

5.Results on the sky

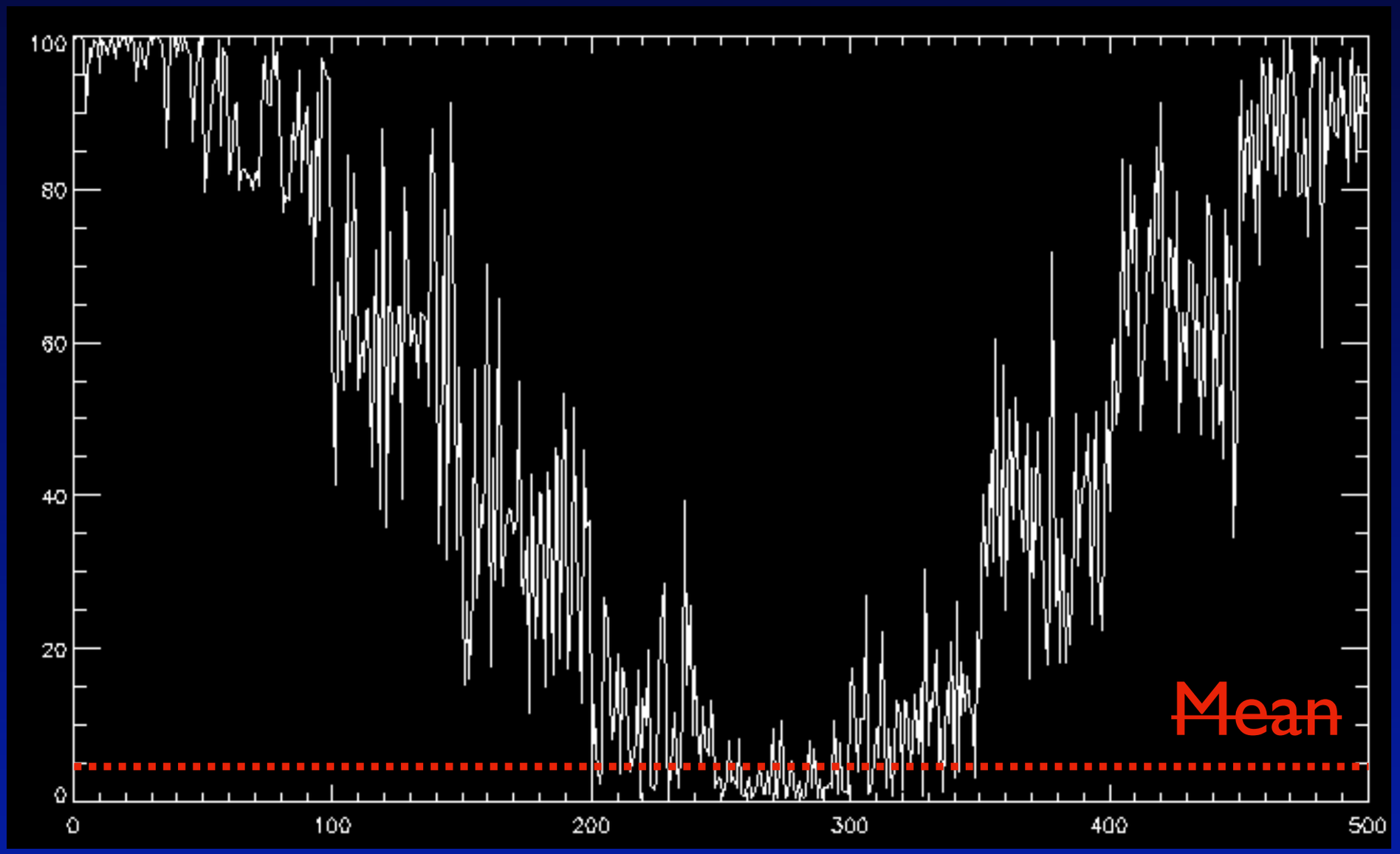
- Measuring a null limited by the observed object
  - ✓ Gamma Draconis, 10.9 mas, Null = 4.7×10^{-2}



Null sequence generated by FNSim

5.Results on the sky

- Measuring a null limited by the observed object
  - ✓Gamma Draconis, 10.9 mas, Null = 4.7×10^{-2}



Null sequence generated by FNSim

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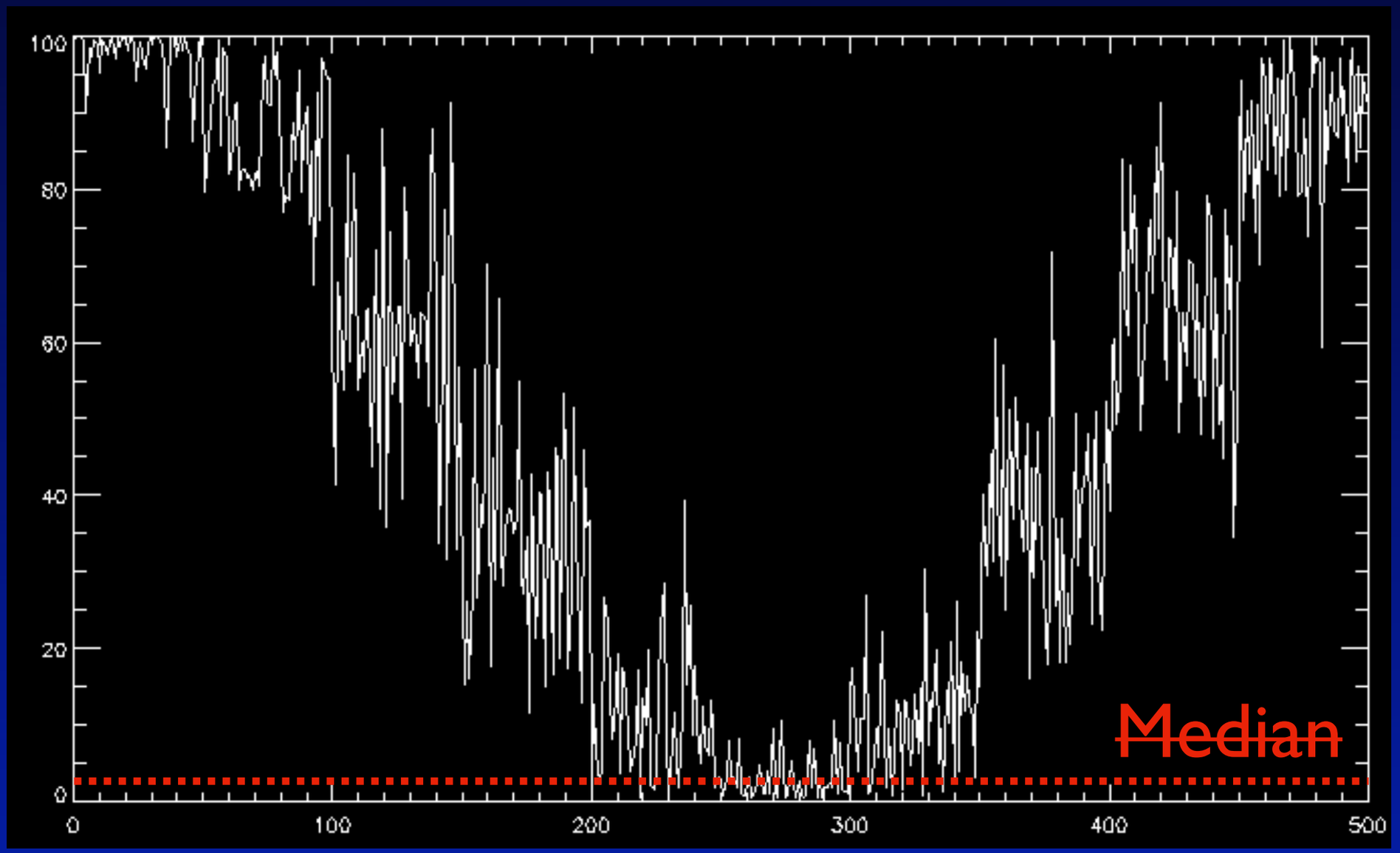
  - ✓Gamma Draconis, 10.9 mas, Null = 4.7×10^{-2}



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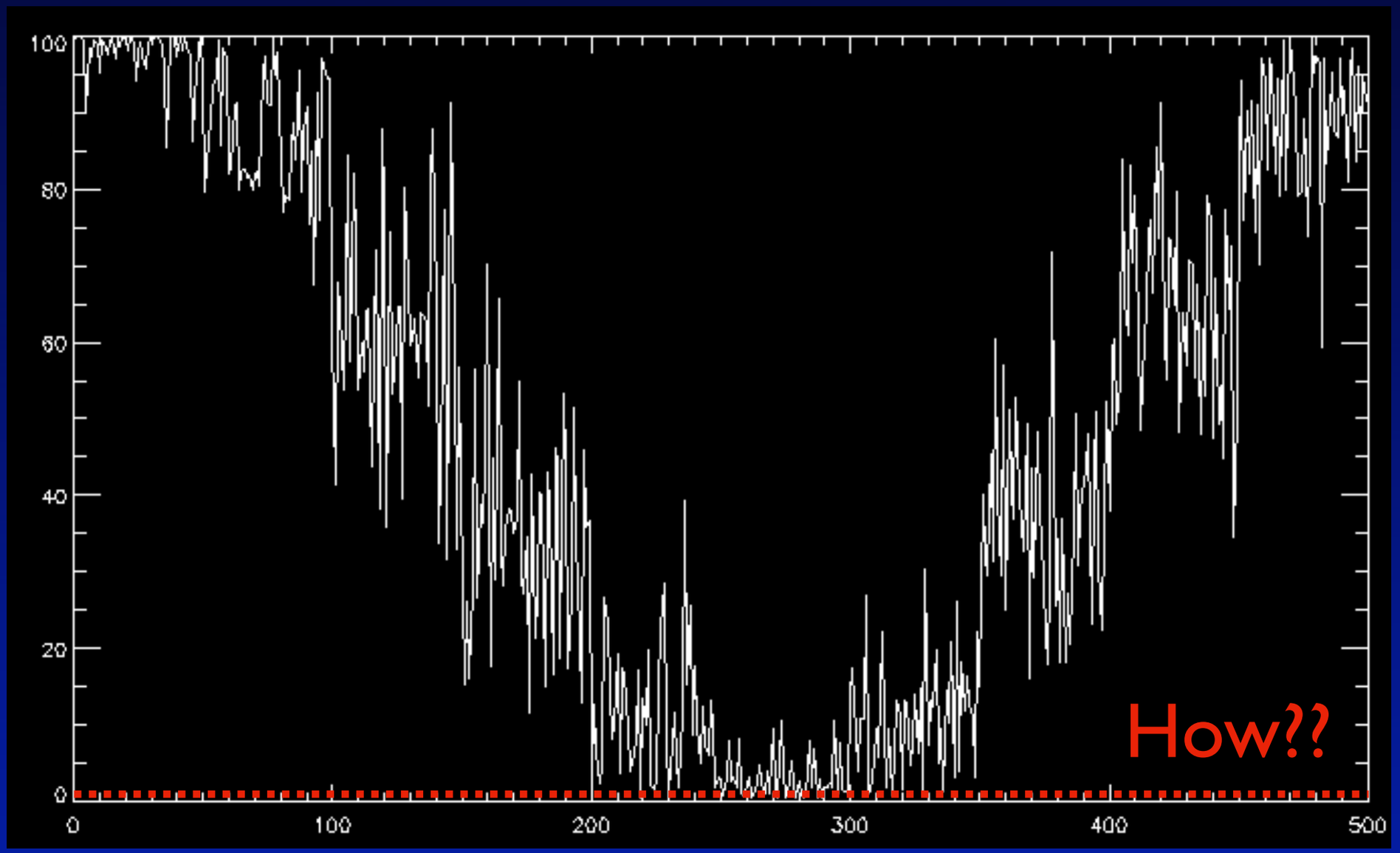
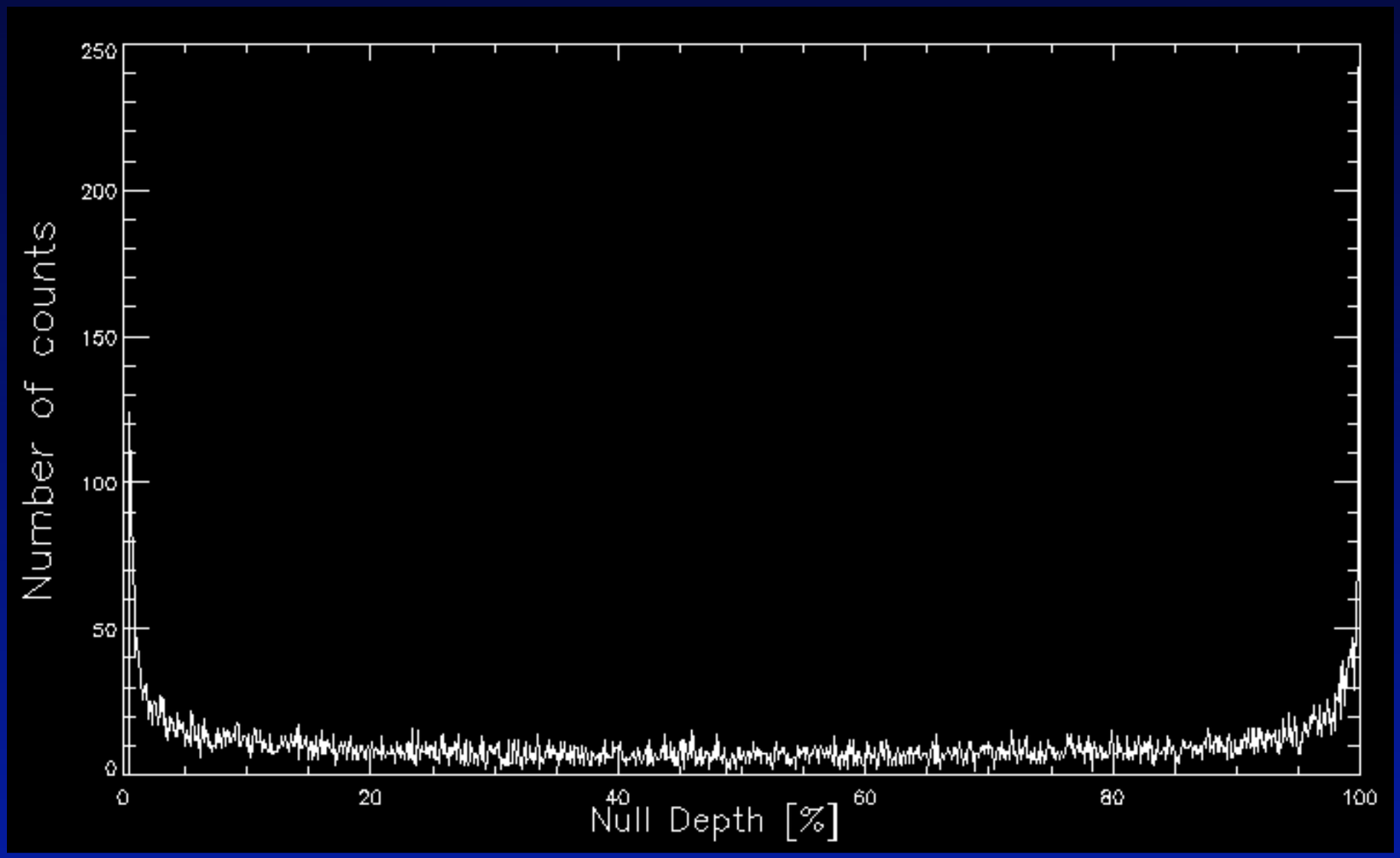
  - ✓Gamma Draconis, 10.9 mas, Null = 4.7×10^{-2}



Null sequence generated by FNSim

5.Results on the sky

- Number of points per null depth interval
- 2 Max: 1 is the null, the other is the contructive fringe



Data obtained with FNSim

5.Results on the sky

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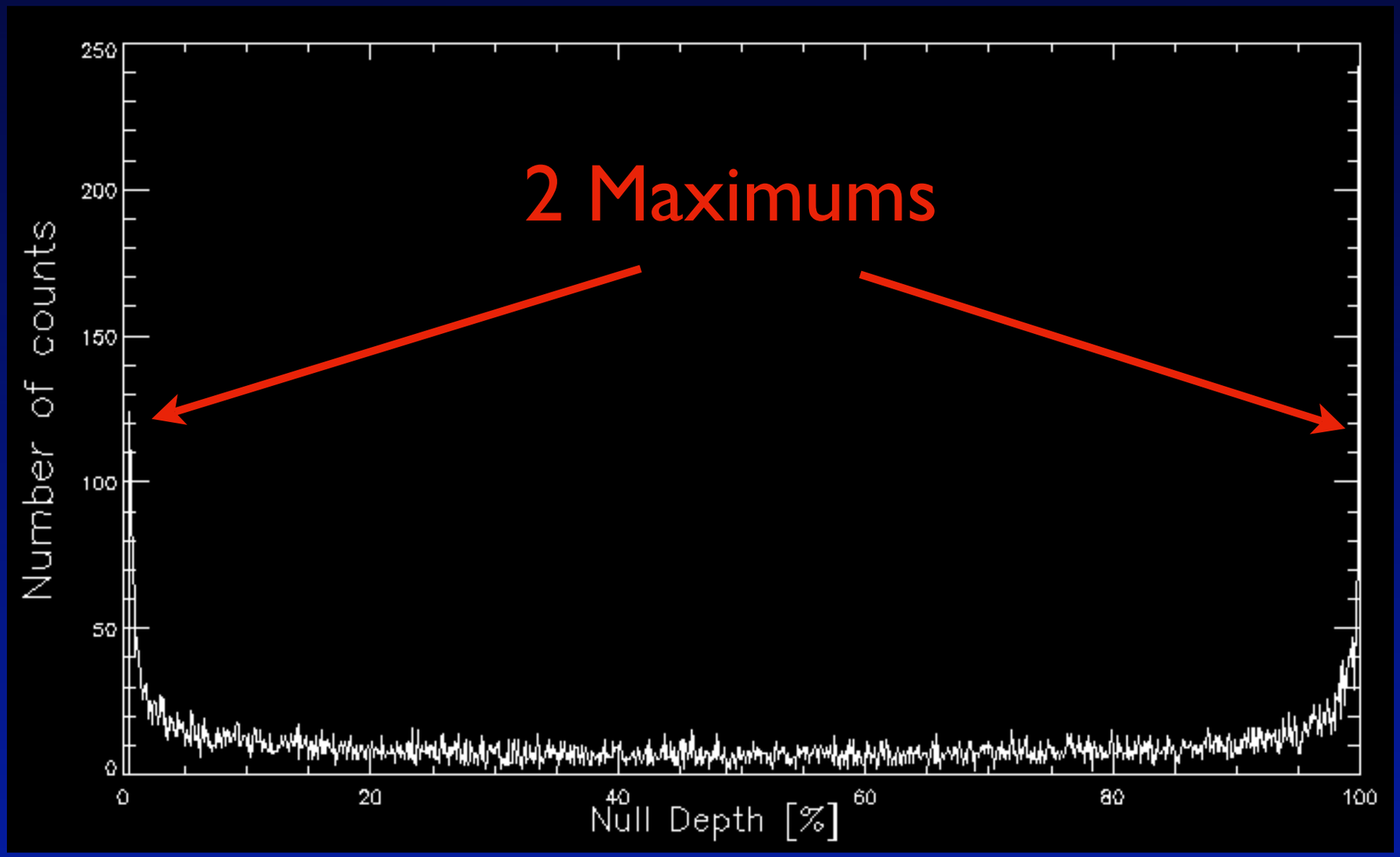

Data obtained with FNSim

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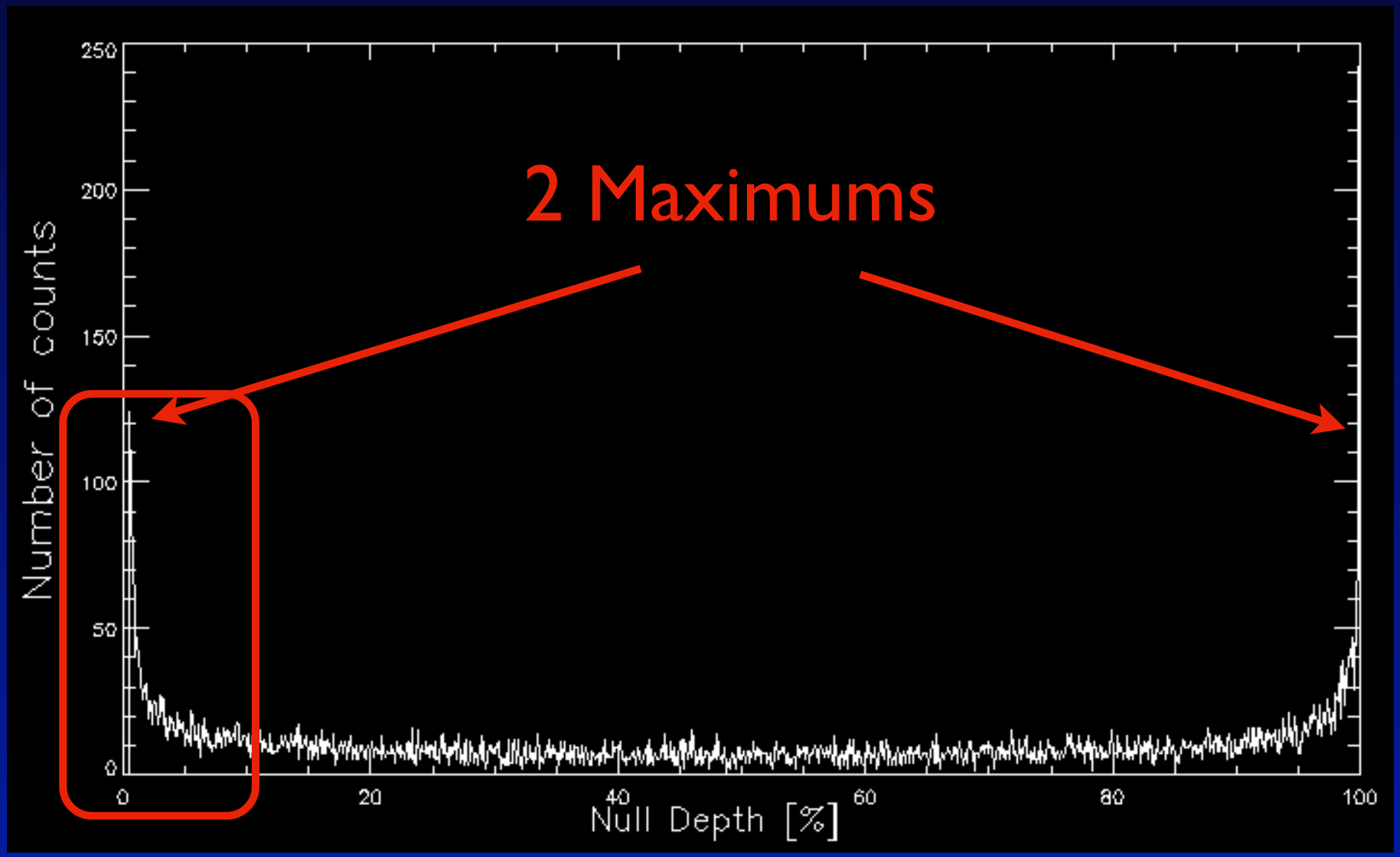
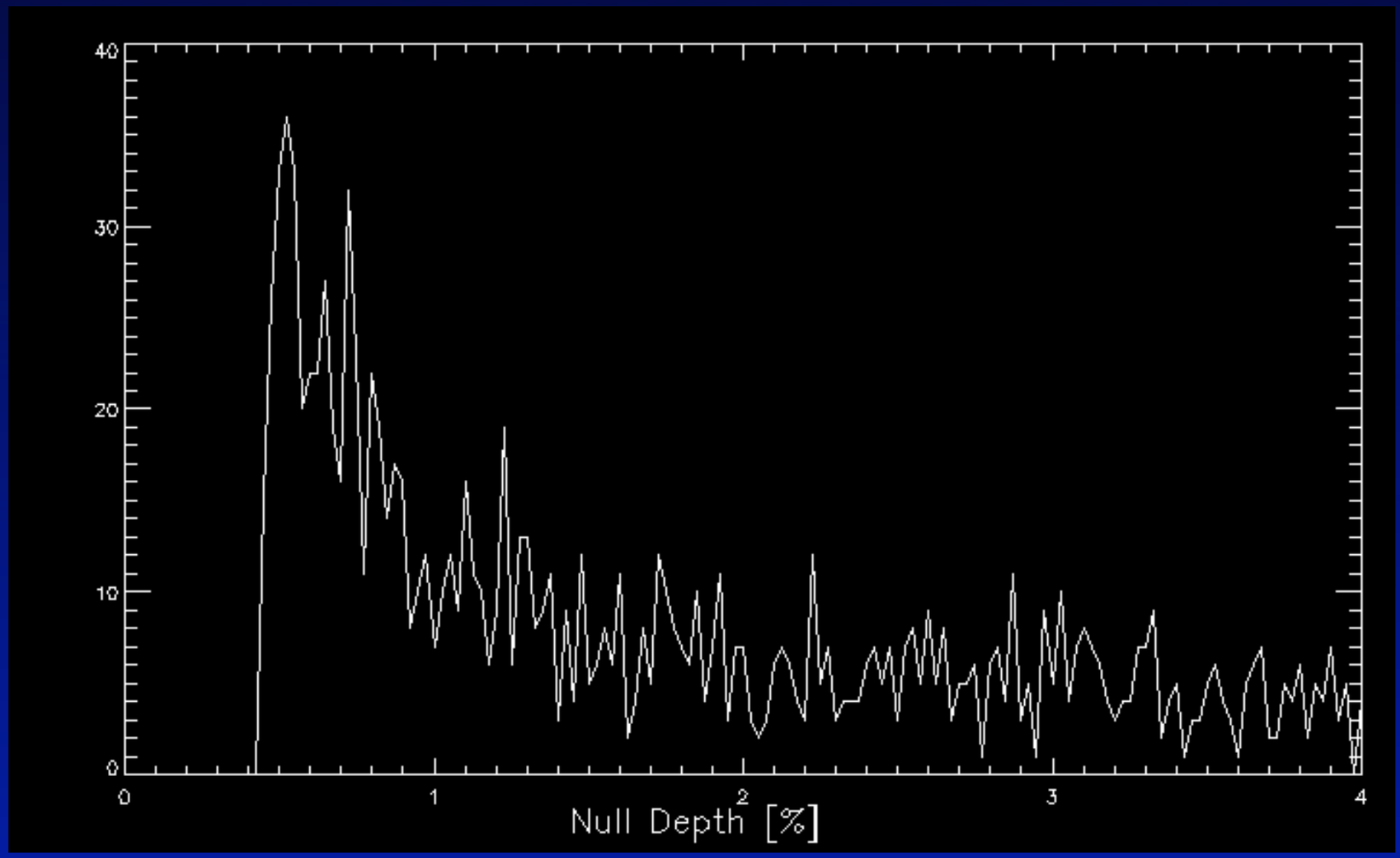
- 2 Max: 1 is the null, the other is the contructive fringe



Data obtained with FNSim

5.Results on the sky

- Number of points per null depth interval
- Null = mid-max point
- Measured null = $4.6 \times 10^{-3} \pm 0.5 \times 10^{-3}$



Data obtained with FNSim

5.Results on the sky

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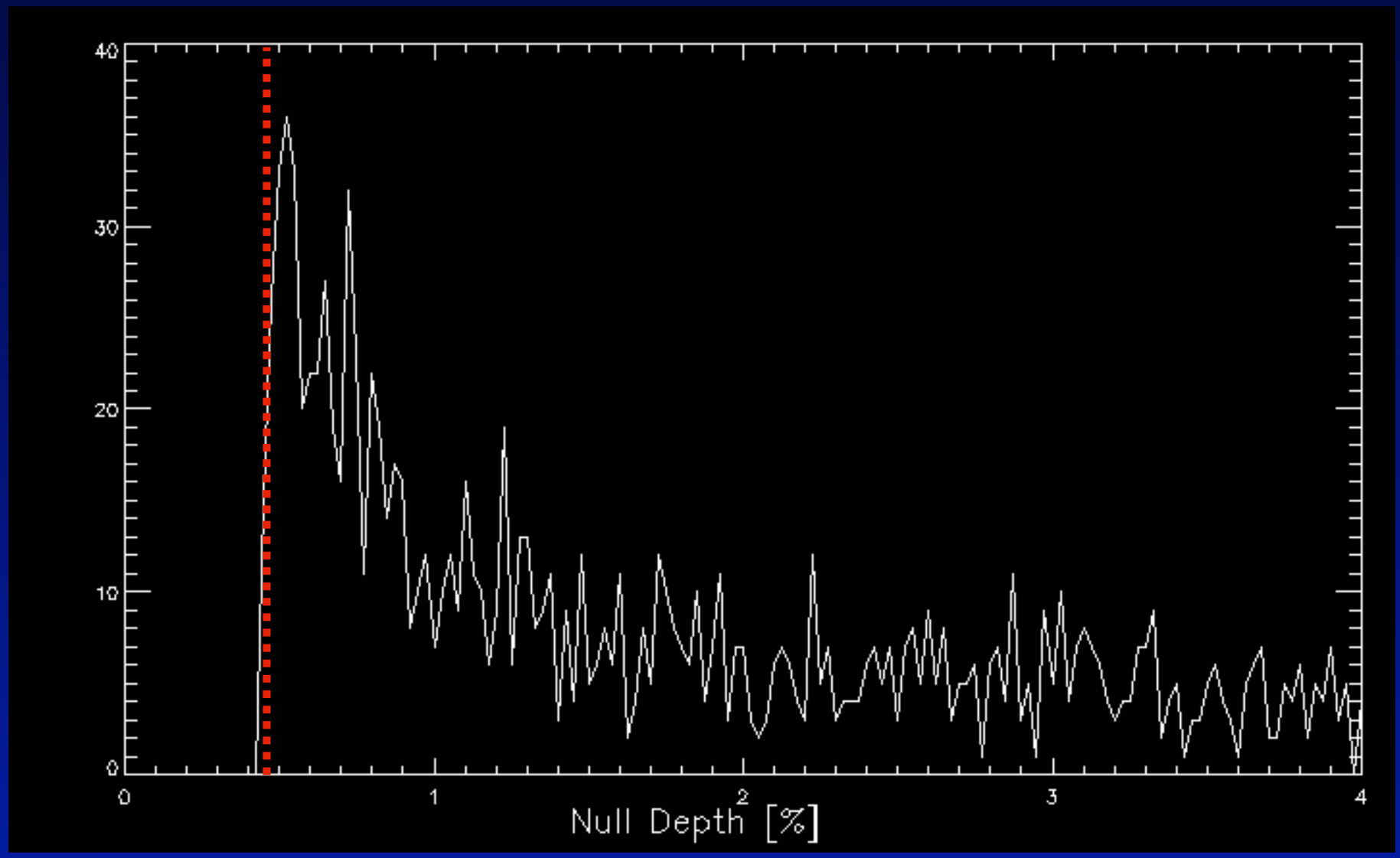

Data obtained with FNSim

5.Results on the sky

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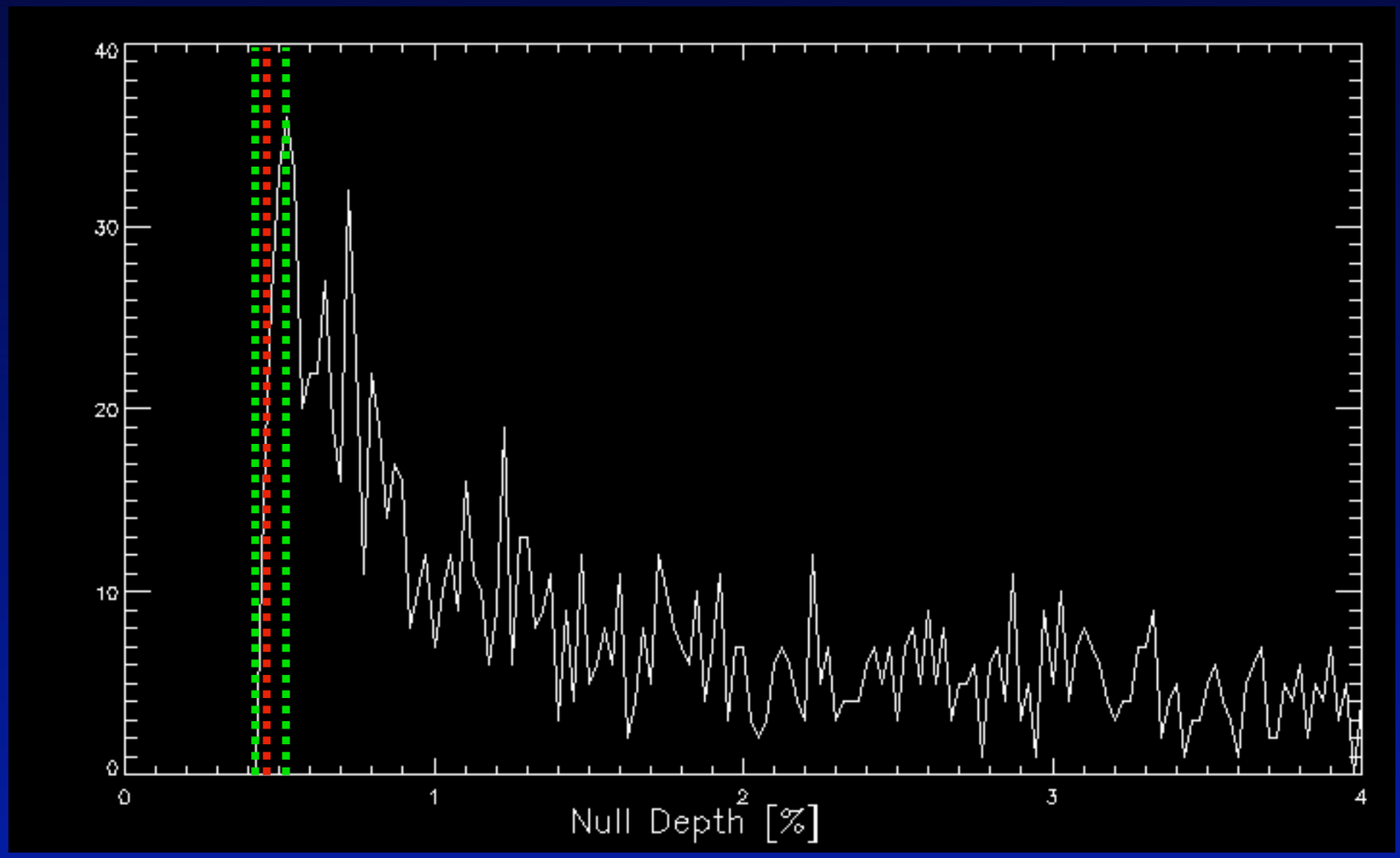
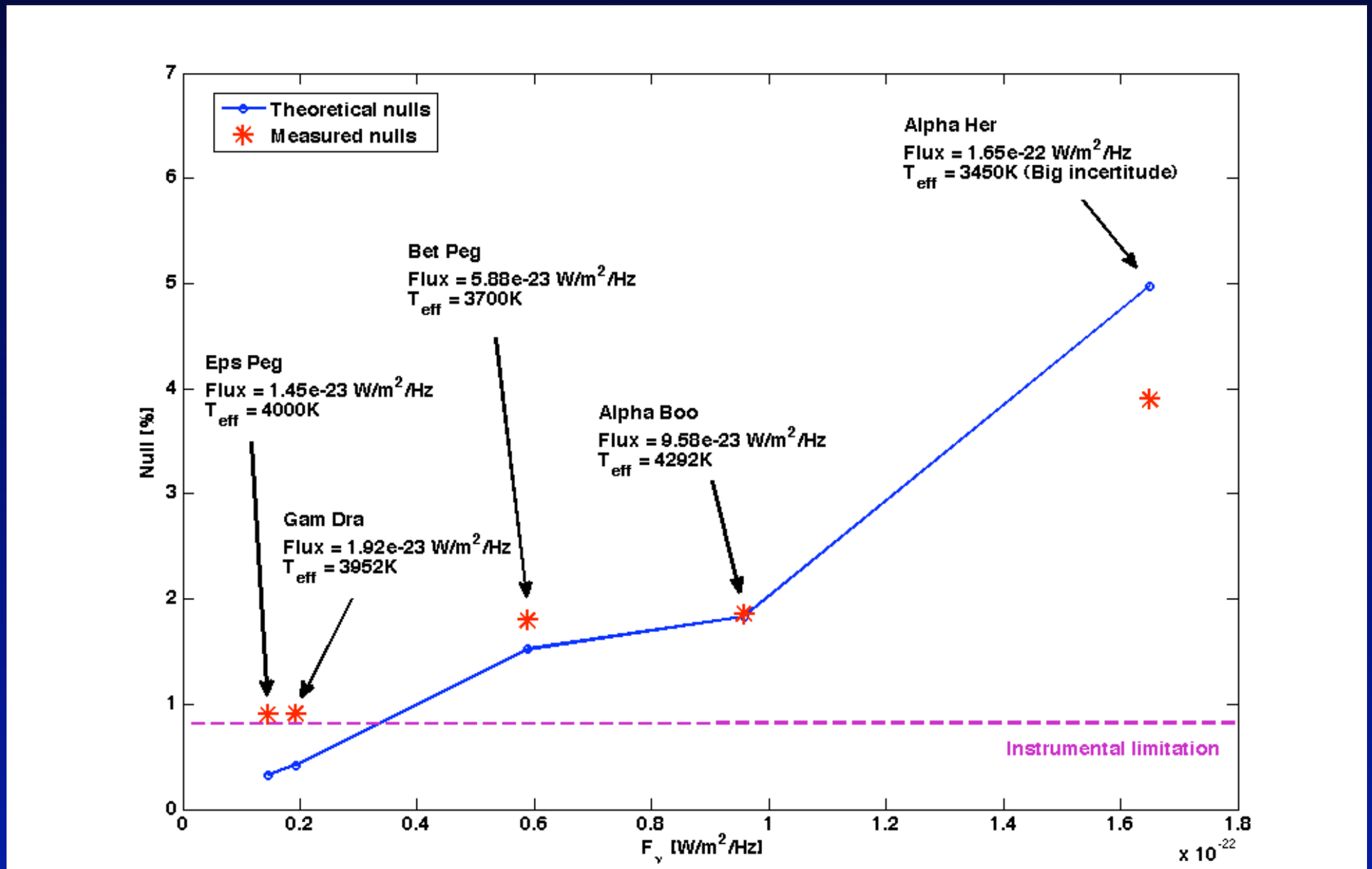


Data obtained with FNSim

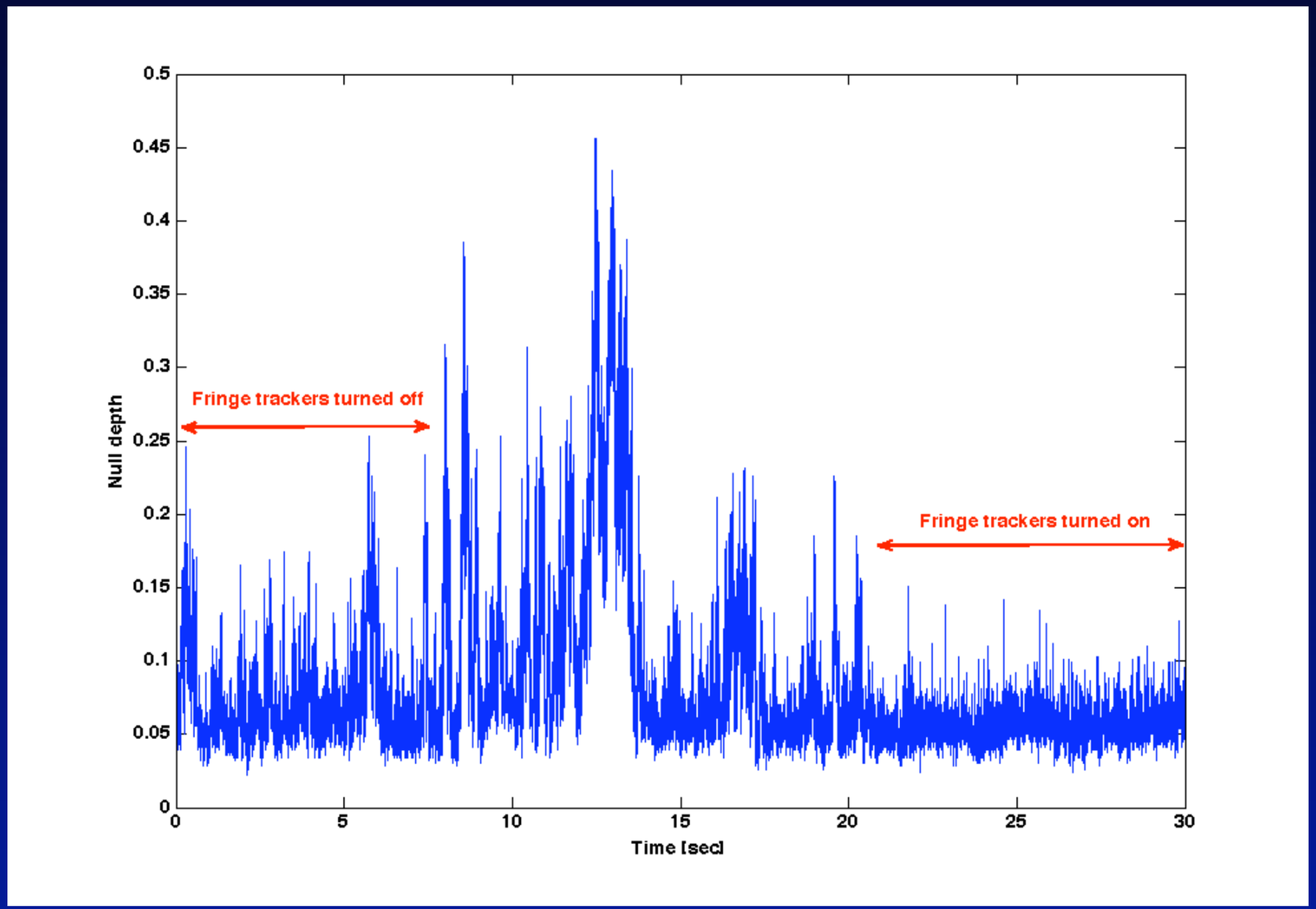
5.Results on the sky

- Scientific results
- 6 Observed star



5.Results on the sky

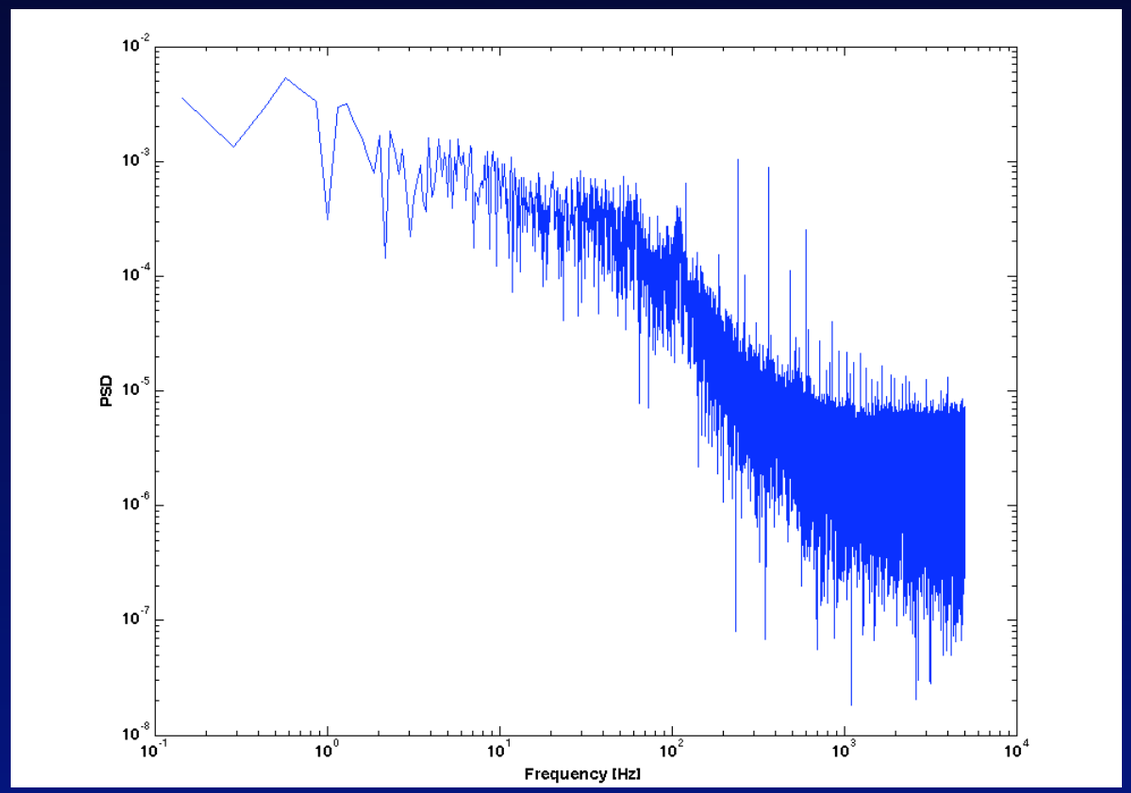
- Impact of the Fringe Trackers on the null



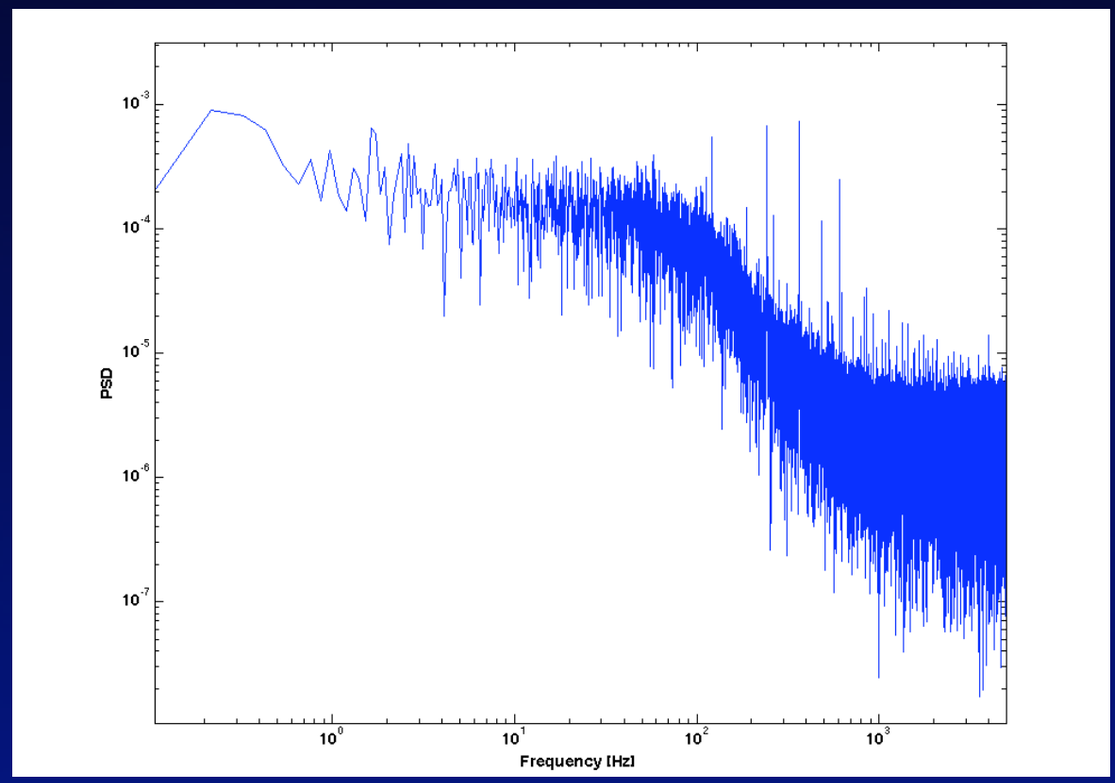
Results obtained at Palomar on Gamma Draconis, July 2008

5.Results on the sky

Fringe tracker OFF



Fringe tracker ON

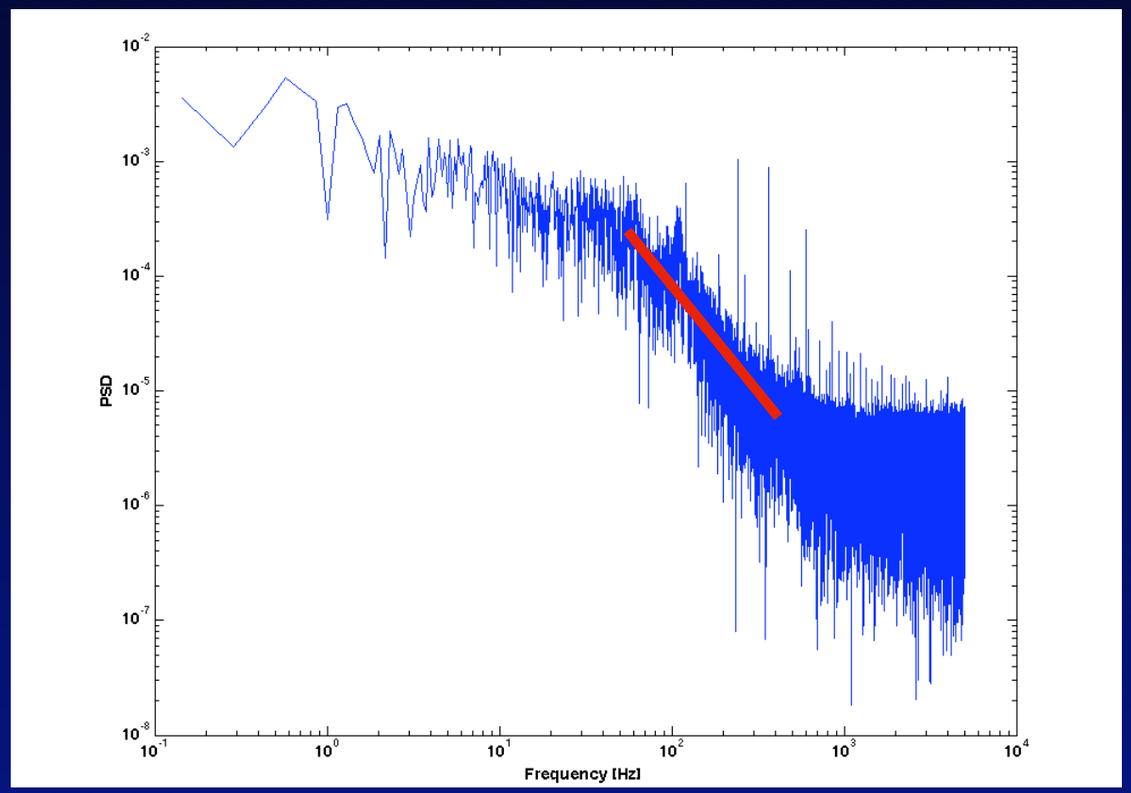


Results obtained at Palomar on Gamma Draconis, July 2008

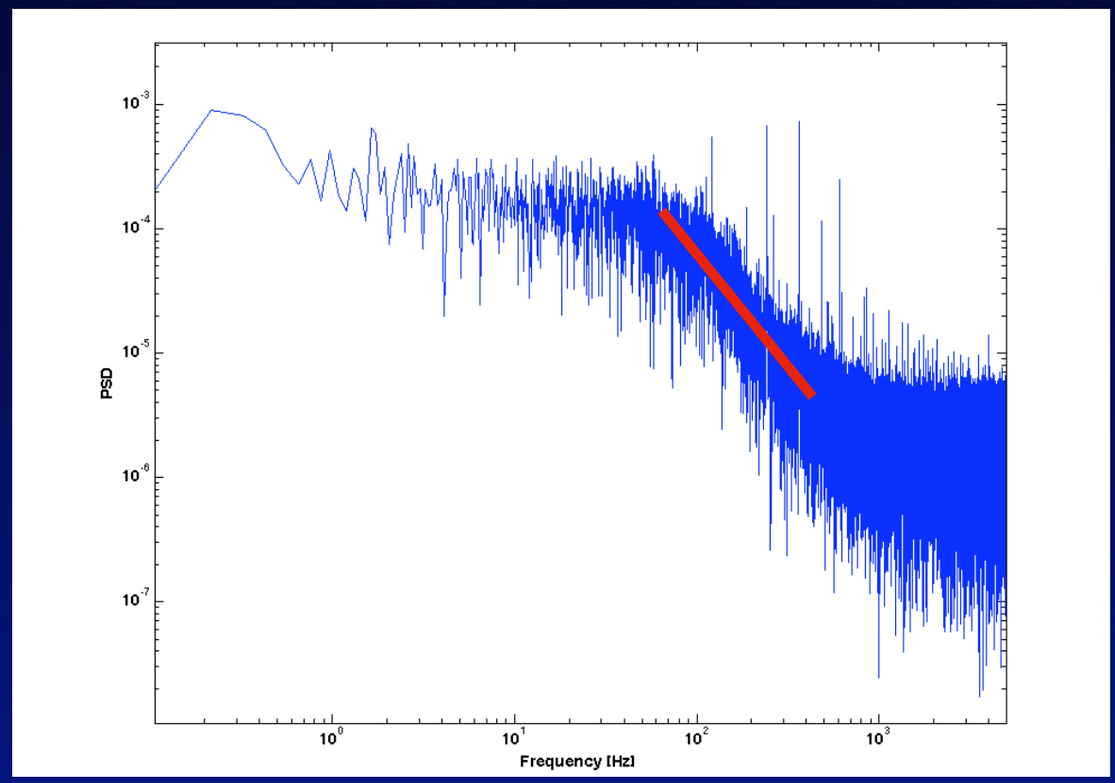
- Fringe tracker cut off frequency: 50-100Hz
- Gain: SNR improved by at least 10
- Improvement: ↗cut off at 200Hz ➡ SNRx10

5.Results on the sky

Fringe tracker OFF



Fringe tracker ON

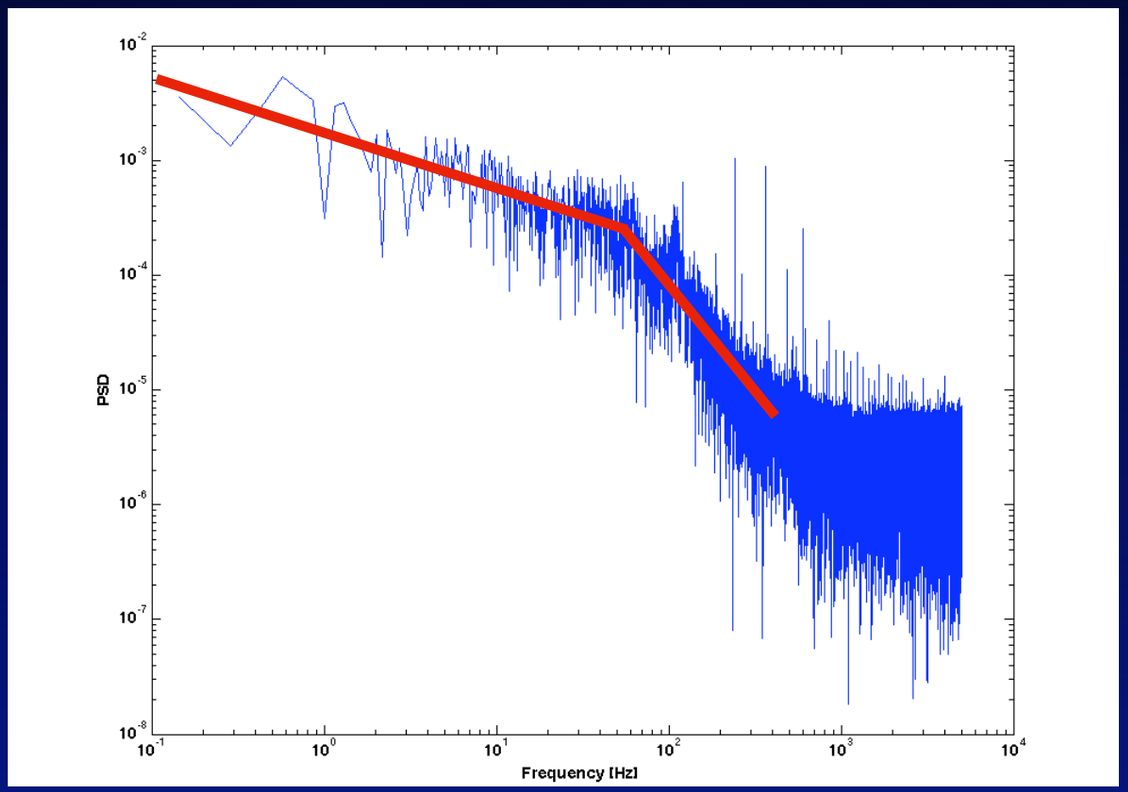


Results obtained at Palomar on Gamma Draconis, July 2008

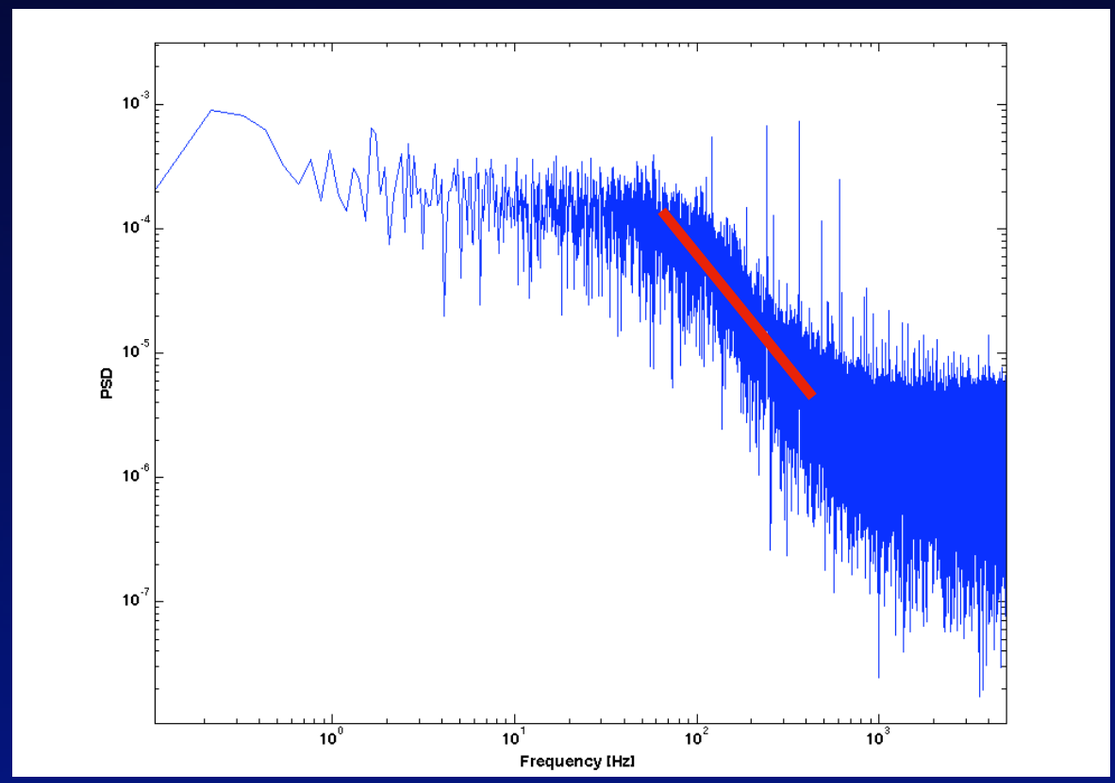
- Fringe tracker cut off frequency: 50-100Hz
- Gain: SNR improved by at least 10
- Improvement: ↗cut off at 200Hz ➡ SNRx10

5.Results on the sky

Fringe tracker OFF



Fringe tracker ON

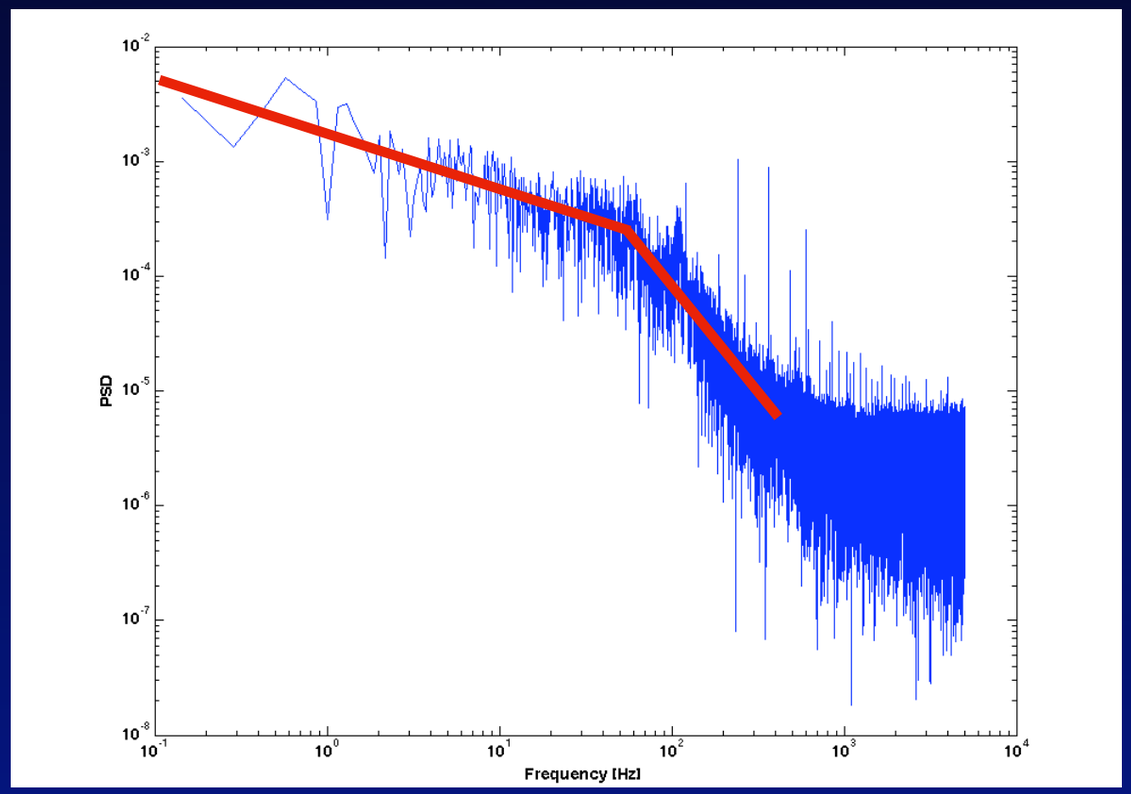


Results obtained at Palomar on Gamma Draconis, July 2008

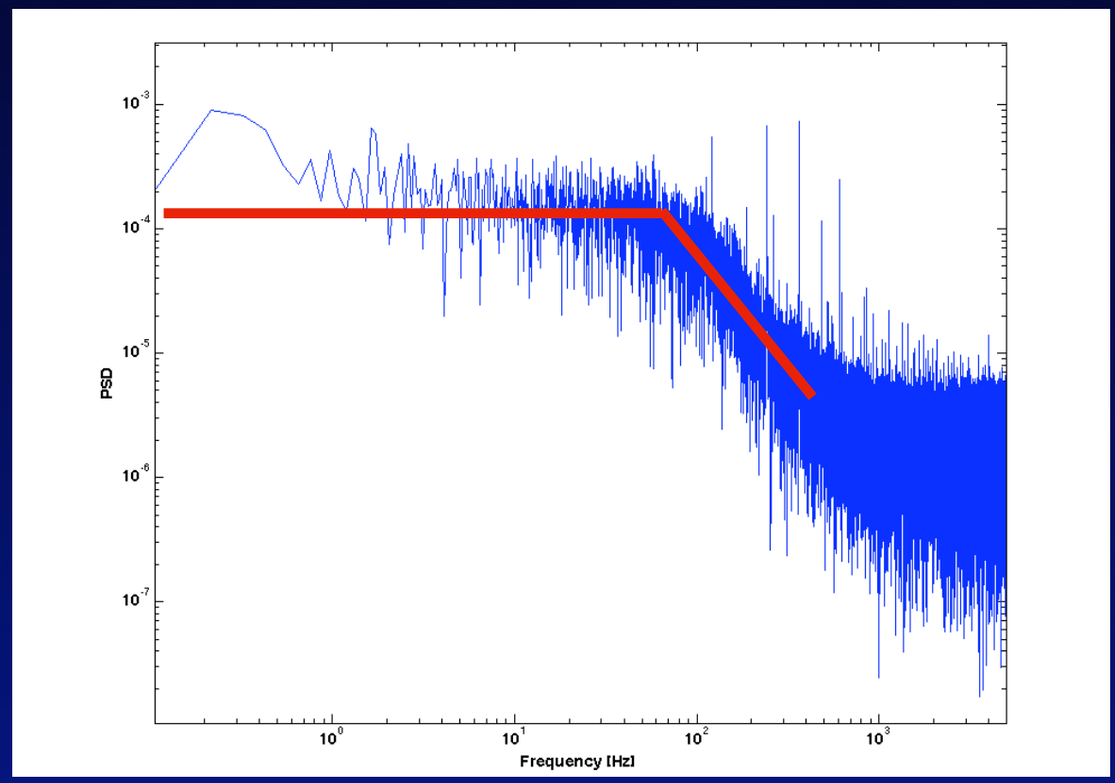
- Fringe tracker cut off frequency: 50-100Hz
- Gain: SNR improved by at least 10
- Improvement: ↗cut off at 200Hz ➡ SNRx10

5.Results on the sky

Fringe tracker OFF



Fringe tracker ON



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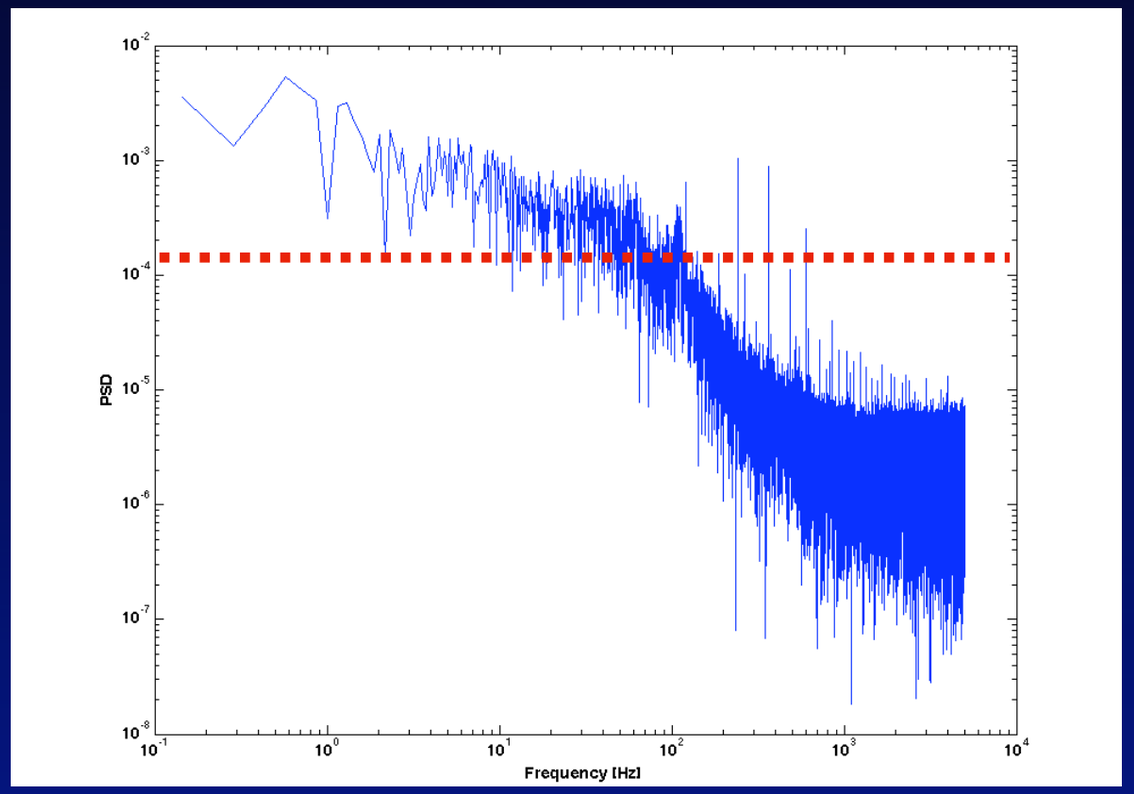
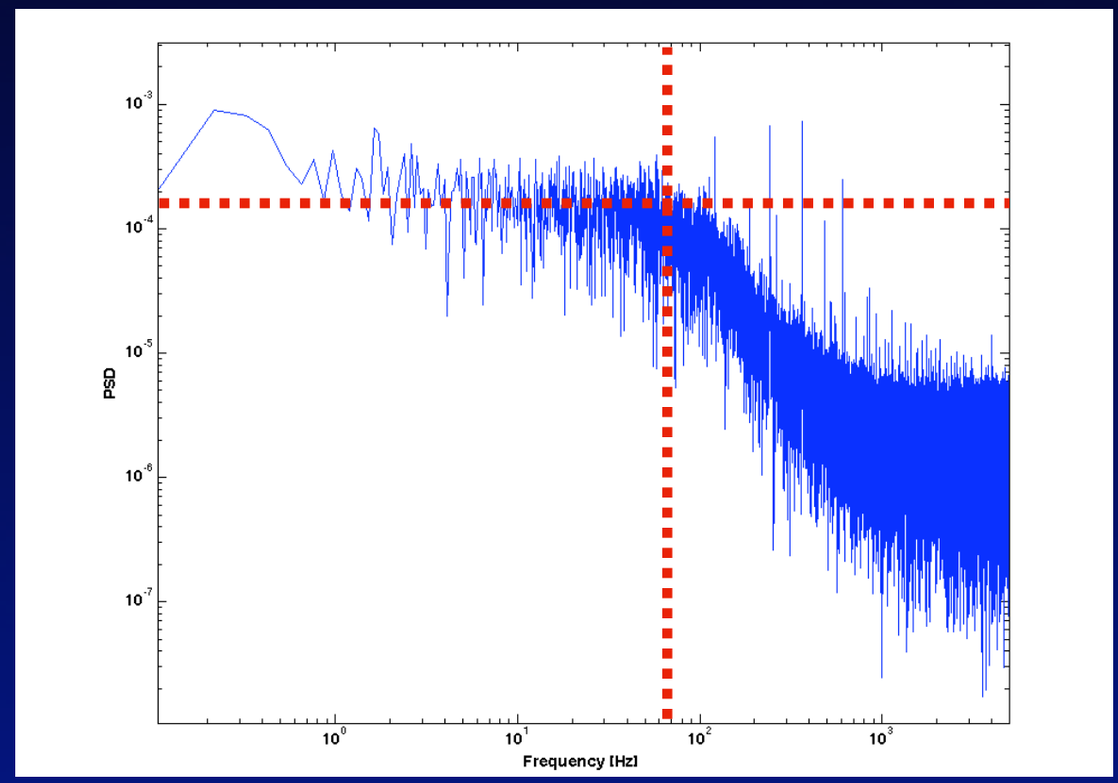


Fringe tracker ON



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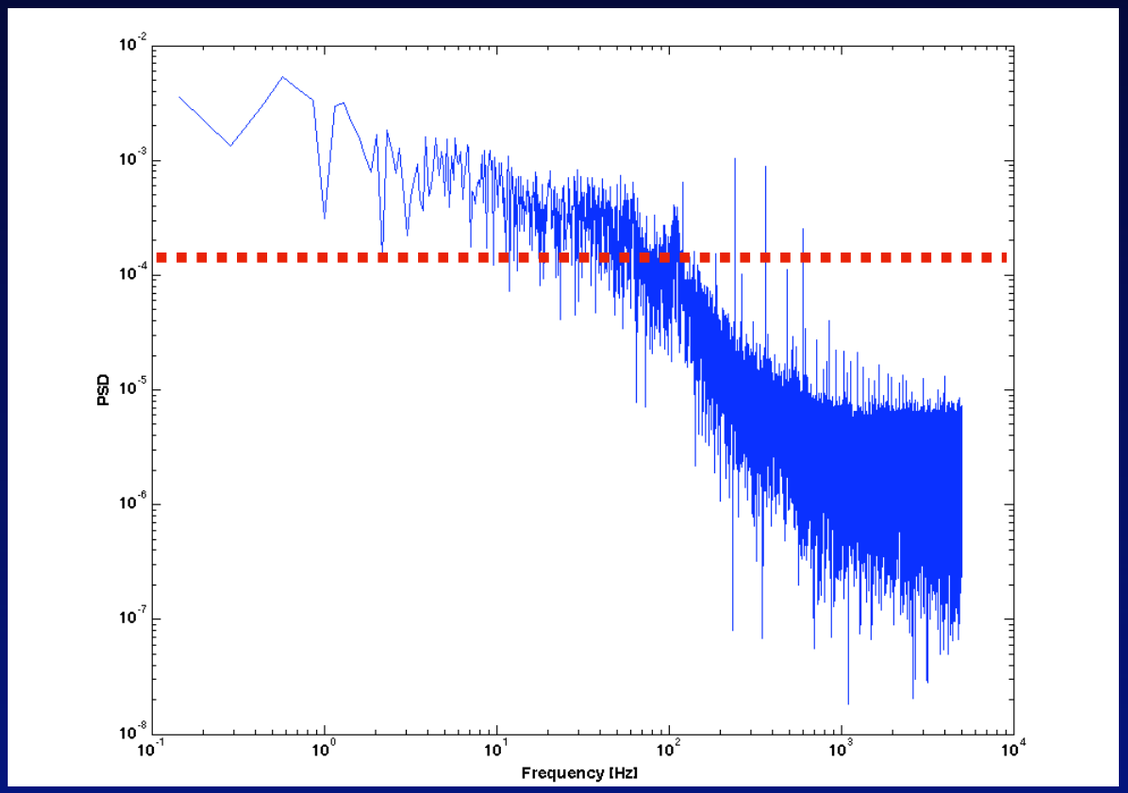
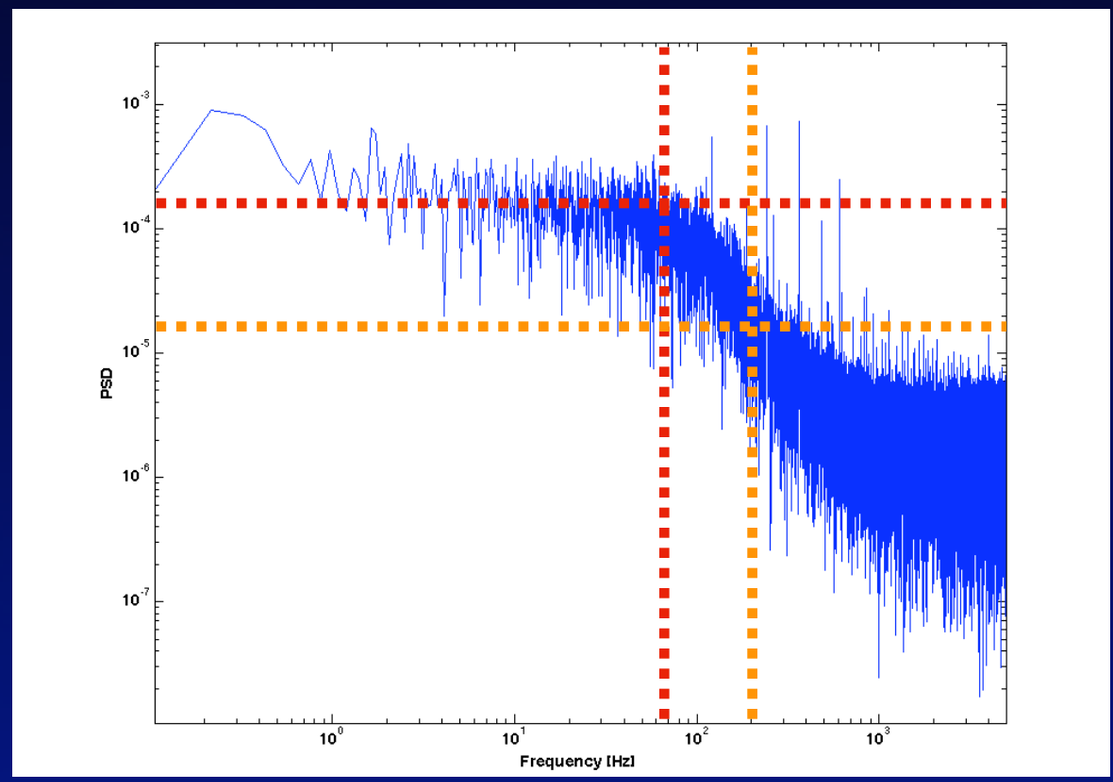
Fringe tracker OFF



Fringe tracker ON

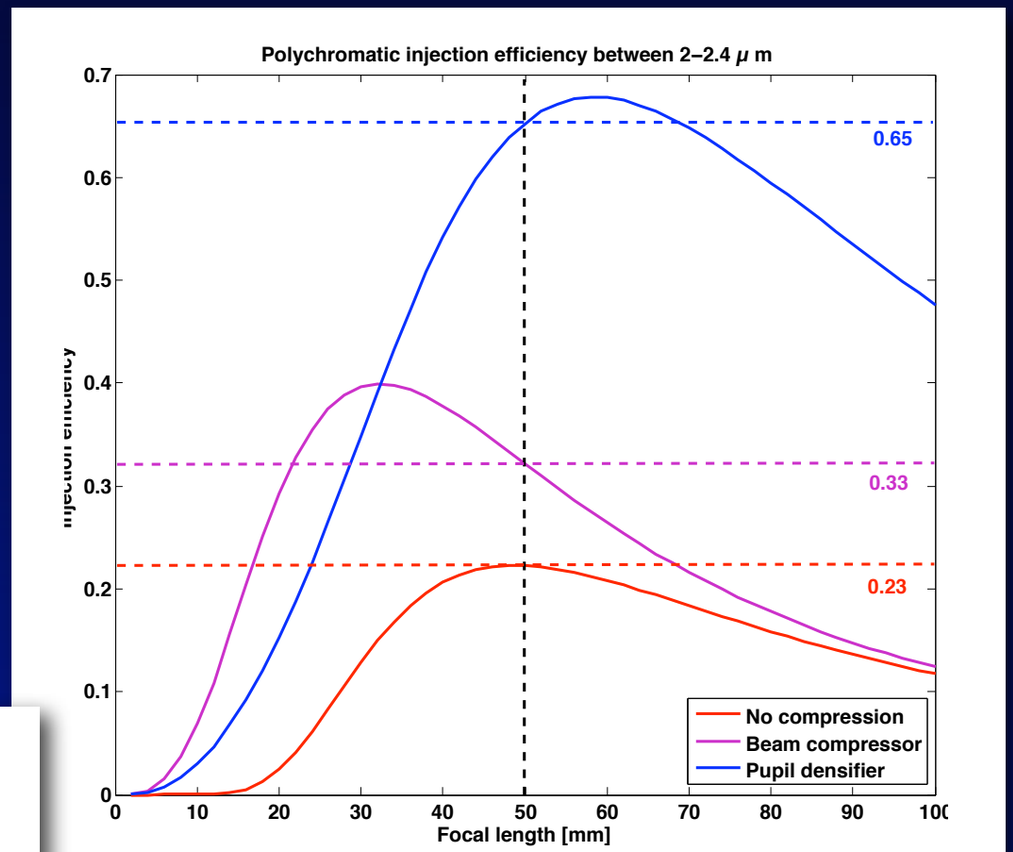


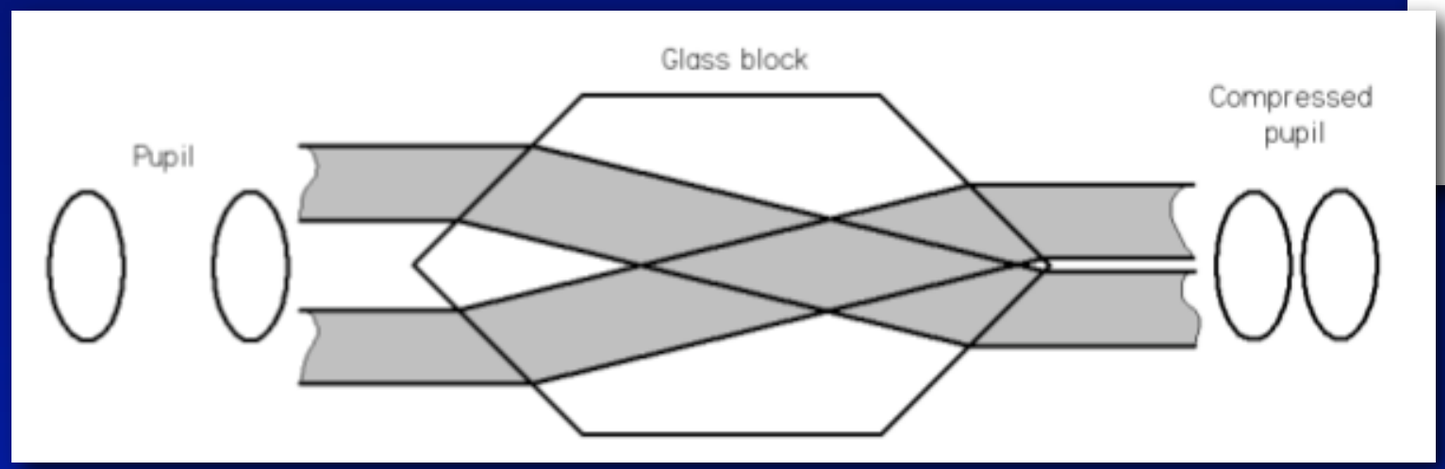
Results obtained at Palomar on Gamma Draconis, July 2008

- Fringe tracker cut off frequency: 50-100Hz
- Gain: SNR improved by at least 10
- Improvement: ↗cut off at 200Hz ➡ SNRx10

6.Future developments

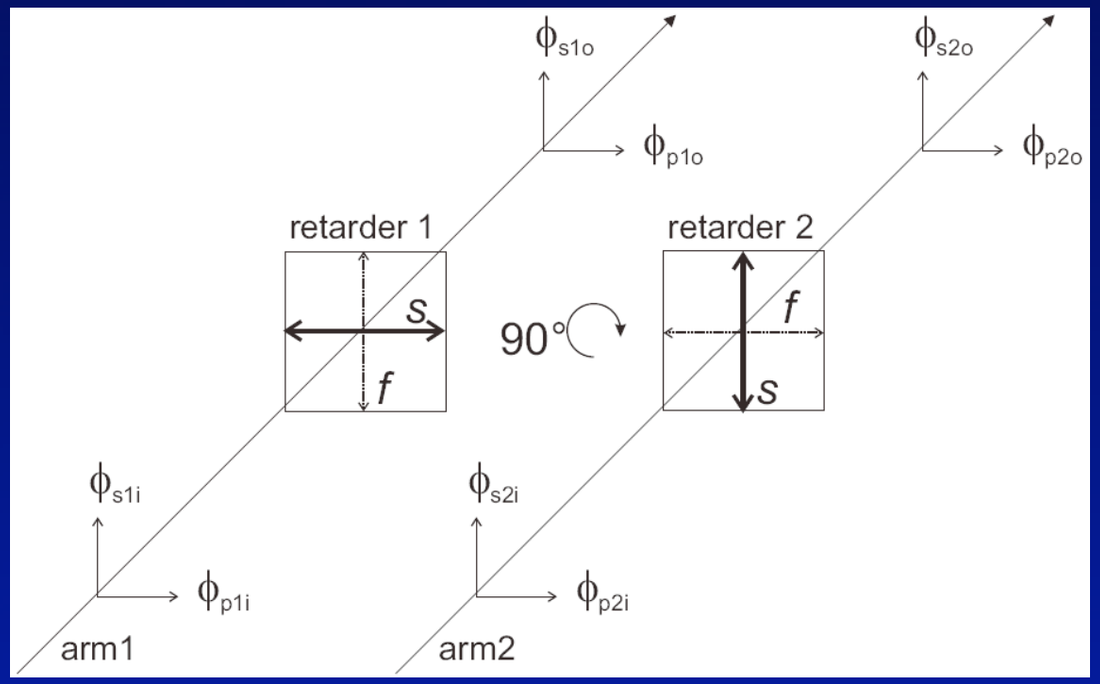
- Improvement of the sensitivity
  - Beam compressor
  - Better detectors
  - Bigger telescope

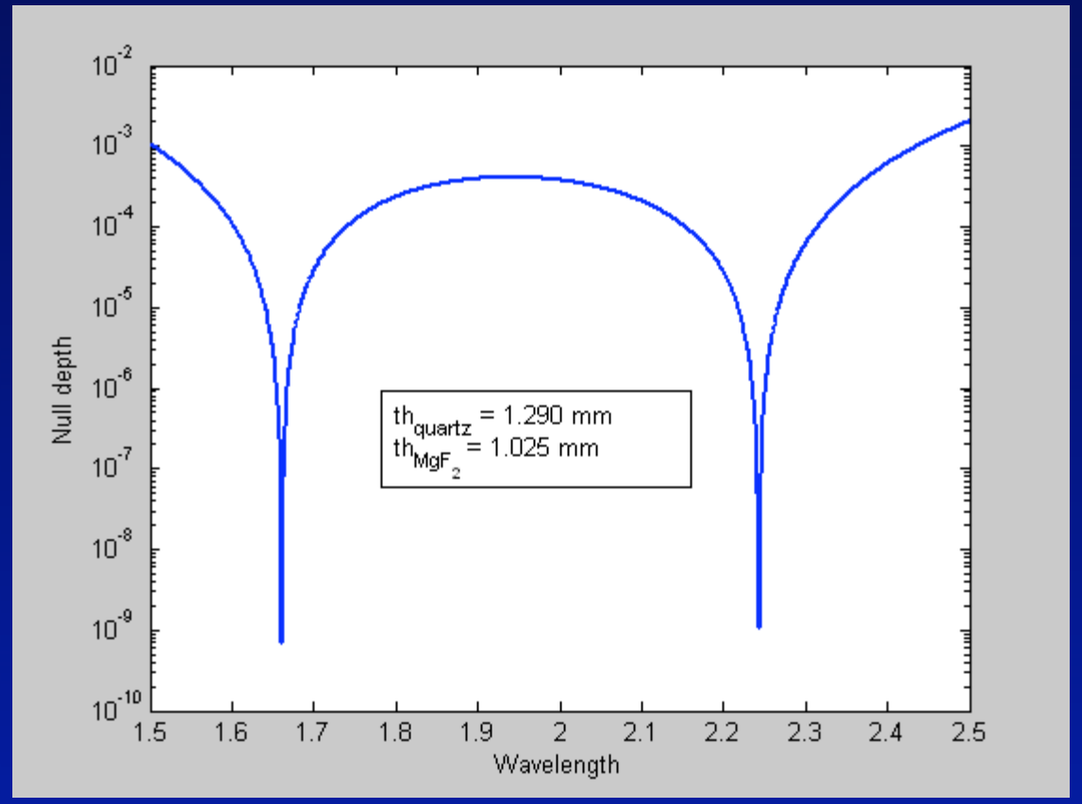




6. Future developments

- Improvement of the achromaticity
  - We are limited by the chromaticity to 2×10^{-3}
  - Achromatic phase shifters (half-wave plates)
  - Possible to go down to 1×10^{-4} in H and K





7.Conclusion

- Multi-axial beam recombination concept is proven
- First successful run at Palomar
- Pupil rotator functionnal
- $1x10^{-3}$ companion detected using pupil rotation
- "Image" successfully reconstructed
- Data analysis strategy under progress
- Ready to observe binaries
- What about a Fiber Nuller on a 8-10 m telescope?
- 4 beams fiber nuller just like TPF-I